 doi:10.20944/preprints202102.0186.v1

Article

Automated gold grain counting.

Part 1: Why counts matter!

Réjean Girard [1], Jonathan Trembaly [1], Alexandre Néron [1], Hugues Longuépée [1]

[1] IOS Services Géoscientifiques Inc, Chicoutimi, QC, G7J 3Y2, Canada; rejeang@iosgeo.com; jtremblay@iosgeo.com; neron.alex@iosgeo.com,: hlonguepee@iosgeo.com

Abstract: The quantitative and qualitative assessment of gold grains from samples of glacial till is a well-established method for exploring gold deposits hidden under glaciated cover. This method, widely used by the industry and which produced numerous successes in locating gold deposits in glaciated terrain, is still based on artisanal gravity separation techniques and visual identification. However, being artisanal, it is limited by inconsistent recoveries and the difficulty to visually identify the predominantly occurring small gold grains. These limitations hinder its capability to decipher subtle or complex signal. To improve detection limits through recovery of small gold grains, a new approach has recently been introduced in the industry (commercially referred as "ARTGold" procedure) using an optimized miniature sluice box coupled with an automated scanning electron microscopy routine. The capabilities of this improved method are highlighted by comparing till surveys conducted around the Borden gold deposit (Ontario, Canada) using the conventional and improved methods at both local and regional scales. Relative to the conventional approach, the improved method recovered almost one order of magnitude more gold grains from samples (regional and down-ice mineralization), dominantly in small size fractions. Increasing the counts in low-abundance regional samples enables better discrimination between background signals and significant dispersions. The method offers an alternative to improve characterization of gold dispersal in glaciated terrain and the related gold deposit footprints.

Keywords: gold; till; gold grain recovery; gold grain size; automated SEM; gold exploration; drift prospecting

---

1. Introduction

Since the dawn of civilization, detrital gold has been recovered from sediments. Gold panning is a skillful art and artisans deserve respect in this regard. But still, this is an artisanal technique, not a science. Tracking dispersion of gold grain in alluvial system has been used for about 200 years by gold panners in search of "mother lode". It grew as a systematic exploration method about 50 years ago when gold grain counting started being conducted in laboratory conditions for mineral exploration companies. Since then, it has been extensively used in glaciated terrain by the exploration industry, and "Drift prospecting" has become the method of choice for grassroots gold exploration in North America and northern Eurasia. However, the method implanted in the 1970's [1, 2, 3, 4], which is heavily dependent on operator's skills and poorly parameterized, barely evolved. The precepts of the method are that gold can efficiently be concentrated with gravimetric method and that gold grains can be easily identified, both of which we here challenge.

The flow of continental ice eroding bedrock produces glacial sediments that inherit the signature of local bedrock sources, including ore bodies [5]. Identification of geochemical and mineralogical dispersal trains within these glacial sediments can therefore be used for tracing

 doi:10.20944/preprints202102.0186.v1

of mineral deposits hidden under glaciated cover. These approaches are particularly relevant for Canada and northern Eurasia where most undiscovered ore deposits are likely buried under the glacial sediments that cover much of the landscape. Important discoveries, such as Douay deposit in northeastern Québec or Rainy River mine in Western Ontario [6, 7] are abundant. Glacial sediment geochemistry and indicator mineral methods have proven to be efficient in drift prospecting for a wide variety of commodities [9-13, 18] and particularly diamonds [14-16]. Nonetheless, these methods are prominently used for gold exploration as it represents the most efficient grassroots method, and also because the bulk of investment in mineral exploration is dedicated for gold (i.e., in 2017, 65% of exploration spending in Canada [17]).

Although gold assaying of glacial sediments represents a far faster and cheaper approach than gold grain counting methods, the information it generates is restricted by the analytical detection limit and is typically erratic due to the nugget effect. In contrast, indicator mineral methods have virtually no detection limit, since unlimited amount of material can be processed, and bypass the nugget effect by counting discreet gold grains regardless of their weight. Furthermore, unlike most other commodities such as diamond, gold itself remains the main indicator minerals for gold deposits [1, 18]. In addition to grain counts, the methods can generate a combination of useful information such as the size, shape, and composition of the grains, which may yield indication on the type of ore deposit and transport distances [19]. In this sense, the recovery of gold grains from glacial sediments and their identification, counting, and characterization, offer a more integrative approach for the exploration of gold deposits in glaciated terrains.

Numerous laboratories offer gold grains counting on a commercial basis. The method used to process glacial sediments in almost all laboratories, hereafter referred as the "conventional method", is based on a combination of gravity separation techniques (mainly shaking tables and hand panning) and visual identification (typically under binocular stereomicroscopes). Although such method is widely used and lead to numerous successes, e.g., [2, 6 ,7, 20-28], some studies also suggest that the conventional method yields erratic results due to low counts and is not effective in recovering/identifying very small gold grains [3, 4, 29-33]. In facts, most laboratories report only an uncertified visual grain count, with grain size estimation and simple shape interpretation [34]. Until recently, such results were taken for granted since it was not possible to benchmark these against more sensitive methods.

The conventional technique is currently limited by the efficiency of the procedure. Regardless of how careful is the laboratory, it is not possible to significantly improve the results beyond the currently used method. Improving the results requires the use of more sophisticated technologies, just as improving detection limits on assays required passage from atomic adsorption to ICP-MS. Recovery and counting of large gold grains is easy. The difficulties arise with recovery and counting of small grains. Therefore, development of more efficient techniques requires focus on small grains, which means simultaneous improvement of both the recovery and identification techniques. Development of counting technique without being capable of recovering the fine-grained gold would be meaningless, and recovering small grain without being capable of counting them would be waste of time and effort. Given that the cumulative proportion of gold grains sharply increases as grain size decreases in unconsolidated sediments [35], the loss of small grains by the conventional method may generate skewed data. Shelp and Nichol [3] have suggested that the conventional method fails to recover 85% to 96% of the gold grains within heavy mineral concentrates from tills of the Canadian Shield.

Improving procedures to increase and systemize the recovery of minute gold from glacial sediments and making the identification of gold grains more robust shall improve the quality and dependability of results. This shall in turn enable optimization of exploration programs, either through overall discovery cost reduction, increasing the rate of discovery in difficult settings, or simply minimizing the rinsk associated with decision process. In the current contribution, we assess an method that enhances the recovery of minute gold grains and

 doi:10.20944/preprints202102.0186.v1

provides automated certified identification. A comparative study between results of the improved and conventional methods is presented, using the Borden Gold project (Newmont Canada, formerly Goldcorp Canada) as example. The implication on exploration, supported by statistical analysis is discussed. The use of detailed data collected from gold grains, such as size, morphology, and chemistry in regard of metallogeny is discussed in companion papers [36, 37].

2. Gold grain size distribution in source rocks

Metallic gold is nearly the only form of gold in ore deposits. Despite the tremendous amount of data on gold deposits in the literature, the gold grain size distribution in mineralized samples is poorly documented to our knowledge. This relates partly to the difficulty of acquiring such information due to gold grain smallness and its erratic distribution that impairs such measurements. Yet, knowing how gold grain sizes are distributed in gold deposits is a premise for the optimization of metallurgical recovery as well as implementation of exploration program in glaciated terrains. So far, only a few studies report information on the gold grain size distribution, suggesting that in most gold deposits, excluding non-pristine placer gold, gold mainly occurs as very minute grains that are difficult to measure and count.

In orogenic gold deposits, which represent the main source of gold production in Canada and Eurasia, e.g. [38, 39], most gold grains appear to be <50 µm in apparent diameter. In a study of the Kalgoorlie ores (Western Australia), the documented gold grains range from <1 to 70 µm with most grains <35 µm [40]. Another study [41] reports that in the Red October gold project (Western Australia) gold grains range from <10 µm to 3,000 µm with an average of 60 µm, and that in the Vivien gold project (Western Australia) gold grains range from <10 µm to 2,000 µm with 50% <300 µm. In the Charters Towers gold project (Queensland, Australia) the same study also reports gold grains between <10 µm and 2,000 µm, with 96% of all gold grains observed in a high-grade zone being <50 µm. In the Cononish gold project (Scotland) the documented gold grains range from <10 µm to 1,200 µm with most <40 µm [41] and in the Nalunaq deposit (Greenland) 80% of documented gold grains are <10 µm [42]. Similarly, a microscopic study of 50 Canadian orogenic gold ores [43] reported that 75% of the gold was fine grained (from 0.1 to 100 µm), with the remaining 25% of the population as coarse grained (from 100 to 10,000 µm); the most common size range of gold grains being 40-50 µm.

The gold grain size appears, in general, to control the gold grade, with low-grade ores containing mainly fine gold grains and high-grade ores containing most coarse gold grains [44]. This grain size/grade relation is suspected to be related to distinct paragenetic stages, with the fine-grained gold responsible for the low-grade background of the ore body and the coarse-grained gold responsible for high-grade clusters [45]. For instance, in the sheeted vein zone of the San Antonio deposit (South America) 70% of gold grains are <50 µm in the low-grade zone whereas only 30% of gold grains are <50 µm in the high-grade zone [46]. However, Haycock's study [43] was essentially on higher grade gold deposits that were producers or potential producers in 1937 and could be more easily processed. Today's gold ores are more likely to be exploited at lower grade (i.e., more difficult to process), dominated by fine-grained gold.

From the grain size distribution in Haycok [43], it was reasoned that submicroscopic gold (<0.1 µm) in orogenic deposits was negligible, as opposed to Carlin-type mineralization in which gold mainly occurs as nano-particles [47, 48]. However, in other styles of gold mineralization, gold grain sizes seem to be similar to those of orogenic deposits. In the Trout Lake VMS (Flin Flon, Manitoba, Canada) 75% of gold alloy grains are < 21µm, with the median being 11 µm [49]. A study of 323 gold grains from 89 thins sections of the Pebble porphyry (Alaska, USA) shows that 96% of them are <15 µm, with an average of 3.8 µm [50]. Similarly, the investigation of 56 gold grains of a core sample of the Grasberg porphyry (Papua, Indonesia) by high resolution X-ray computed tomography reveals that the grains range from 7 to 43 µm [51]. Finally, it was reported that 411 Au alloy grains in a sample of the Au-horizon of the Skaergaard Complex (Greenland, Denmark) range from 1.6 to 56.9 μm, with an average of 22.6 μm [52].

Through the last 30 years, results were accumulated from ore petrography studies on a wide variety of gold occurrences located in Abitibi and James-Bay, Superior Craton, Canada [59]. A total of 4316 gold grains (figure 1) down to 1 μm in diameter, of which 3934 were smaller than 100 μm, were measured on hundreds of thin sections from a large variety of mineral occurrences. Measurements were made with an eyepiece graticule on a petrographic microscope (Zeiss AxioImager M2m, Neofluor objectives, 1000x and Leitz Laborlux-2, Fluotar objectives, 500x or 1200x OEL). Measurement method has been consistent through time, conducted by the same petrographe (Mm. Lucie Tremblay) and smallness is limited by optical resolution (about 0.4 μm, or 1 μm grain). Measured diameter is expected to be slightly underestimated, since polished surface of the grains are not necessarily truncating the largest portion of the grains, and no stereological correction were made [Wang et al, 53]. It is considered that these represent an in-situ gold grain population that is representative of Archean orogenic or intrusion-related deposits susceptible to have been eroded by glacier and dispersed in glacial sediments. Despite its numerous bias and limitations, this population can be considered as the most representative reference to compare with gold grain characteristics extracted from glacial sediments.

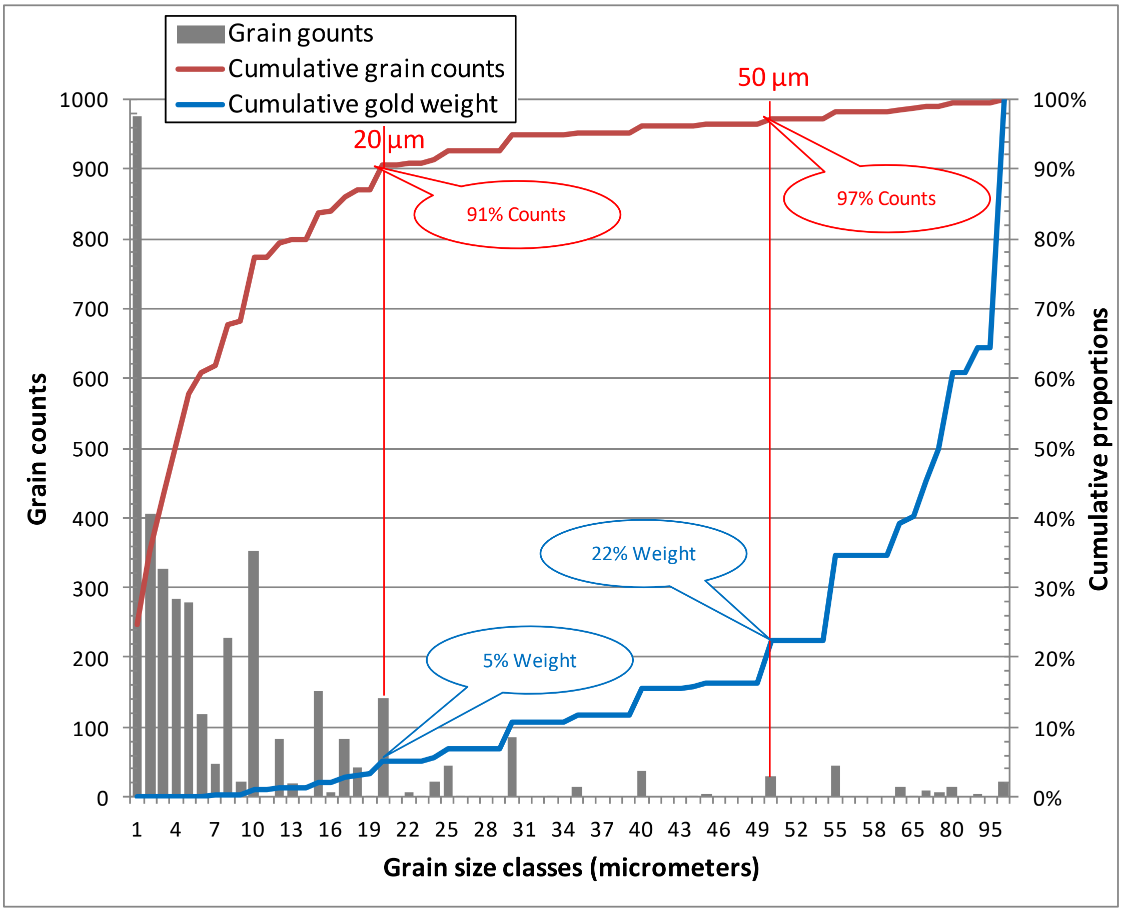


Figure 1: In-situ gold grain size distribution in rocks from Archean syn-orogenic gold deposits of the Superior Craton, Northwestern Québec and Northeastern Ontario, Canada. Measurements on 3934 gold grains smaller than 100 μm were conducted over a 20 years period by the same mineralogist (Mme Lucie Tremblay) from hundreds of polished thin sections with the use of a reflected light petrographic microscope. Grain counts are indicated by grey bars on right scale, while cumulative distribution is indicated by red curve on right scale. The blue curve is the cumulative proportion of gold weight calculated from grain size assuming a spherical shape. While grain counts are overwhelmingly dominated by small grains, the bulk of gold weight is contained in large grains, which explains the good metallurgical recovery despite the poor grain recovery of most gravimetric concentration methods.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

References at 20 and 50 µm are indicated. Notice the size scale is skewed for large grains, and grains larger than 100 µm were excluded of cumulative proportions.

Grain size distribution in rocks usually follows a log-normal distribution [56, 57, 58, 54]. Gold grain size distribution is expected to follow such law, a hypothesis that been verified in a few deposits by the author and other groups [55]. The current grain population approximates such distribution, with a log-average of 4.9 µm and a variation coefficient of 0.8. About 80% of the measured grains are smaller than 20 µm (longest apparent axis) which is the commonly accepted smallest size recovered in glacial sediments by conventional gravimetric methods. Furthermore, only 12% of the grains are larger than 50 µm, which represent the recovery collapse of the usual gravimetric separation methods. This grain size distribution is heavily skewed toward small grain, but this is not reflective of gold abundance itself. The weight of contained gold in a grain is a nearly cubic function of its size, and consequently small grains do not account for a proportional weight of gold despite their abundance. Since large grains are easy to recover, this leads to a fair (>80%) metallurgical recovery by gravimetric methods, despite a poor grain count recovery. And as far as mineral exploration is concerned, the information extracted from the grain is more significant than the mere weight of the gold, which is more easily obtained simply from assays.

After erosion, gold grains are dispersed in secondary environment along with all other minerals. In alluvial systems, small gold grains are likely to be elutriated and size distribution is not representative anymore of the initial gold in mineralized samples. Glacial till, which essentially consists of sub-glacial grinded sediments not affected by hydraulic transport, is not significantly affected by elutriation process regardless of the transport distance [19]. Accordingly, till has been sampled for decades in gold exploration programs and regional surveys, and numerous studies e.g. [2, 7, 60-63] have highlighted that, like in ore deposits, most gold in till is fine-grained, with a maximum rate of occurrence around 30-50 µm while using the conventional method. However, most data collected for exploration purpose do not includes accurate size measurement, limited to size brackets estimation only.

2.1 Improvement on Concentration Methods

The efficiency of gold grain counting is dependent on the ability to recover gold from glacial sediments and to correctly identify them. Whereas the sampling of glacial sediments is a well-established protocol [64, 65], sample processing still relies on artisanal techniques (e.g., hand panning and visual identification), results of which varies between laboratories or operators and has underrated limitations and reliability issues. Many studies suggest that the conventional method used to process till samples fails to recover/identify most of the small grains [3, 4, 29-33].

In most laboratories, glacial sediments are wet sieved at 1 or 2 mm and passing material is conveyed through a gravity separator, usually a shaking table of various design, although some other devices, such as a centrifugal concentrator (*Falcon* or *Knelson* concentrator), spiral concentrator (*Goldhound*), elutriation columns, dense media separator or various type of mechanized panner (*Superpanner, rotating cones*) can be used. The purpose of this operation is to wash away the light and clay-sized particles and concentrate the heavy silt- and sand-sized ones. Most of these devices can reduce the size of a sample from tens of kilograms of sediments to a few tens of grams of heavy minerals with a particle size ranging from 5 µm to 1-2 mm. These heavy minerals concentrates (HMC) are not suitable for efficient gold grain visual sorting, being too large and thus time consuming to sort. Consequently, in most laboratories, HMCs (or preconcentrates) require further concentration, which is typically conducted by hand panning, reducing the weight to a fraction of a gram. Although gold panners can be surprisingly skilled, panning remains an artisanal process which is not parameterized and very difficult to conduct in a rigorous and systematic manner. Since gold grains smaller than 50 µm are barely visible with a mineralogist hand lens, the panner relies solely on the presence of the larger grains to evaluate its work. Consequently, recovery of small grains, which is already poor with the shaking table, is susceptible to become anemic on subsequent panning.

The efficiency of gravity separation techniques on gold grains is influenced by a combination of intrinsic parameters of the gold grains (smallness, flatness, porosity, roughness, attachments, coating etc) and extrinsic parameters related to the sediments that contains them (grain size distribution, bulk density, agglomeration, clay abundance, etc). The prominent factor is the hydrophobic character of gold since all these processes are conducted in water. Improper wetting of the surface of the grain prevents the grain from sinking, the surface tension being larger than the gravity pull on the grain. This leads to gold flotation and escape in overflows [3, 4, 29-33]. This issue is apparently dominating the recovery collapse below 50 µm.

Improving the recovery of gold grains, more specifically minute ones, has been achieved with the development of a set of procedures (Figure 2) on a specially designed sluice, hereafter referred as “fluidized bed” (Figures 3). The device is a micro-corrugated channel in which a strictly lamellar flow of water is maintained (Figure 3a). The fluidized particle load is maintained by vibrating the sluice. Vibrations are accurately tuned to maintain particles in suspension and trap free-running denser gold grains in the micro-corrugations, without clogging the riffles. Maintaining particles into suspension prevents micro-corrugations overfilling without necessitating vigorous water flow and enables efficient elutriation of light minerals. This approach works better than a shaking table for which optimization and reproducible conditions are difficult to maintain, considering the sediment feed being non-homogeneous from samples to samples. However, recovery of >250 µm gold grains is not optimal with the fluidized bed due to the size of micro-corrugations This issue is bypassed by installing the fluidized bed as a feeding apron to a shaking table where coarse gold grains can be recovered with other large heavy minerals. Processing a 10-20 kg till sample with the device box takes approximately 40 minutes and produces a super-concentrate of 20–200 mg. This represents a single-pass concentration factor of 40,000×–600,000×. This operation does not require a hand panning finish, which makes it less dependent of the operators’ skills. As magnetite is dense and abundant, it tends to be concentrated with gold by the optimized sluice box. The magnetic fraction of the super-concentrate is removed with a hand auto-magnet to further enhance the concentration factor.

Proper preparation of the material cannot be underrated. Prior to be fed to the fluidized bed, the sample needs to be slurred with water and a wetting agent. Defloculant is usually not required to process glacial sediments as they do not contain clay minerals. Then the slurry is fed into a stack of mechanized wet-sieving units allowing to separate the <1 mm till fraction from coarse material. Coarse particles have to be removed, since they will cause turbulences hindering proper separation in the fluidized bed. Sifting the material in the field is not recommended, since it would likely cause the lost of fine grains. Also, the sampled material must be free of iron or carbonate coating to ensure proper liberation of the grains, and thus shall not be affected by pedogenic processes.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

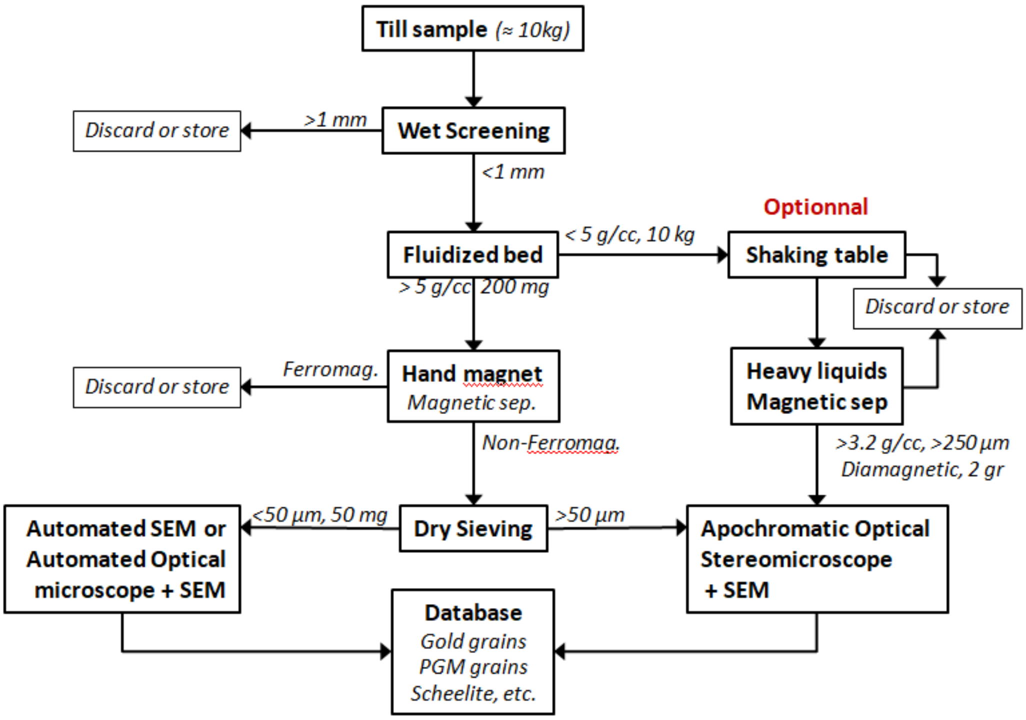


Figure 2. Schematized flow chart of the till sample processing of the improved method. Note that the optimized sluice box can be placed as a feeding apron to a shaking table to recover gold grains or other heavy minerals larger than 250 µm.

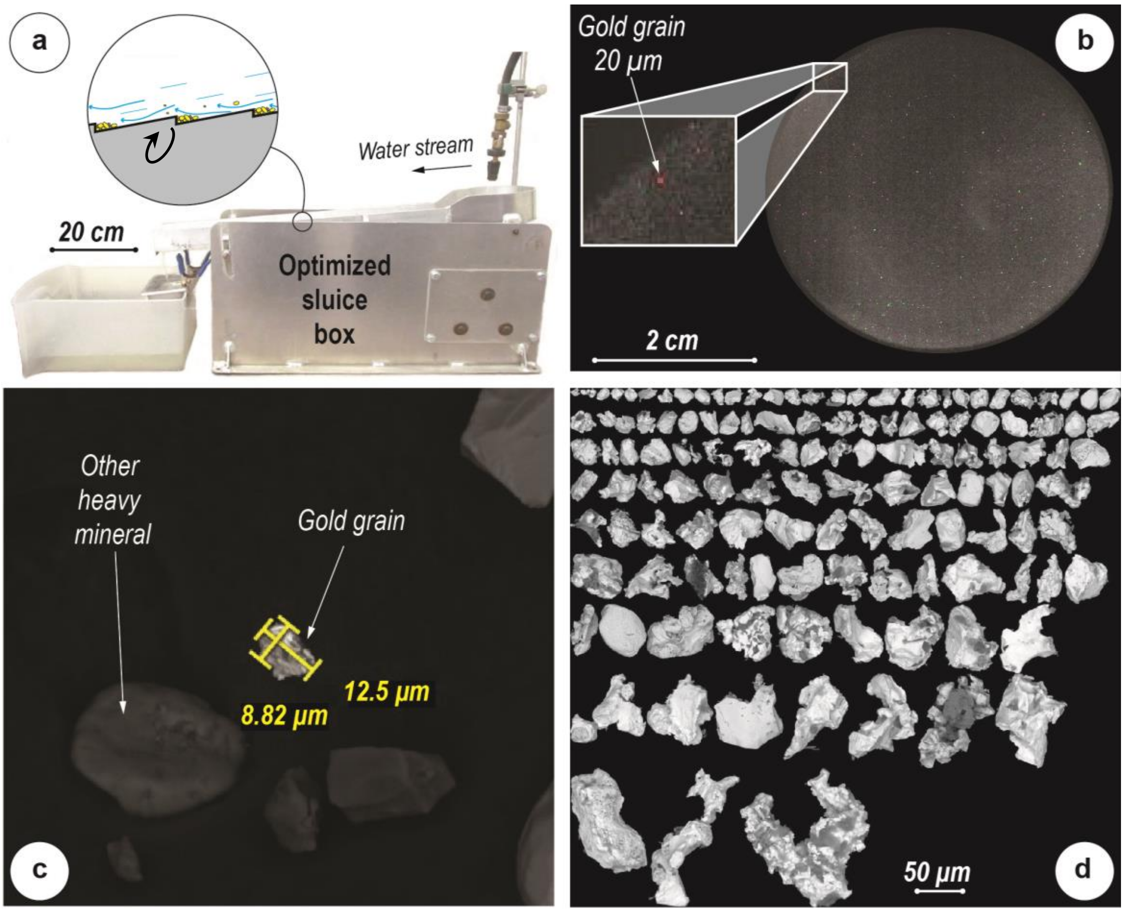


Figure 3. Key features of the improved method (**a**) the fluidized bed used to concentrate the grains (the cartoon illustrates the behavior of gold grains in the lamellar hydraulic flow and

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

elliptical motion of the bed); (**b**) Example of a custom-made holder dusted with the <50 µm material (bright spots are the heaviest minerals); (**c**) Example of high magnification backs-scattered electron image of a gold grain (among other heavy minerals) used for size measurement; and (**d**) Example of an automated back-scattered electron image mosaic of gold grains recovered from a single till sample. Gold grains as small as 2 µm in equivalent diameter can be recovered.

2.2 Improvement on Gold grain counting

The second misleading premise of the conventional approach is that gold grains are easily recognized amongst heavy mineral concentrates. While recognizing large gold grains is easy even for untrained geologist, properly identifying tiny specks is matter of endless debate. Typical 10-16x triplex mineralogist hand lens enable a resolution of a few tens of micrometers, thus limiting the reliable identification of a gold grain to about 50 µm, the size of a human hair. However, heavy minerals cannot be practically sorted with hand lens, and the task is usually carried under stereomicroscope.

Most laboratories use stereomicroscopes with planachromatic objective that enable magnification up to 40x, at which they are plagued with persistent chromatic aberration and limited depth of field, meaning they are usually operated at 16x to 25x. Regardless of the perceived quality of the optic, identifying gold grains <50 µm with such microscopes remains a tricky task (figure 4). High-end apochromatic stereomicroscopes offer a better resolution, enabling higher magnification, but are not in common usage in most commercial laboratories. Working at high magnification (100x) limits the field of view as well as depth of field, slowing the sorting process, without mentioning the difficulty to manipulate the grains and the fatigues it causes to technicians. Tests made by trained mineralogist sorting the same concentrates using high-end apochromatic stereomicroscope, compared to usual planachromatic stereomicroscope, increased the gold grain counts by 57% for grains in excess of 50 um (Figure 5). Although some laboratories routinely report gold grains in the 20 um size range, verification done with an SEM on such grains indicated high (up to 70%) misidentification rates with brass chips and sulphides mistaken for gold.

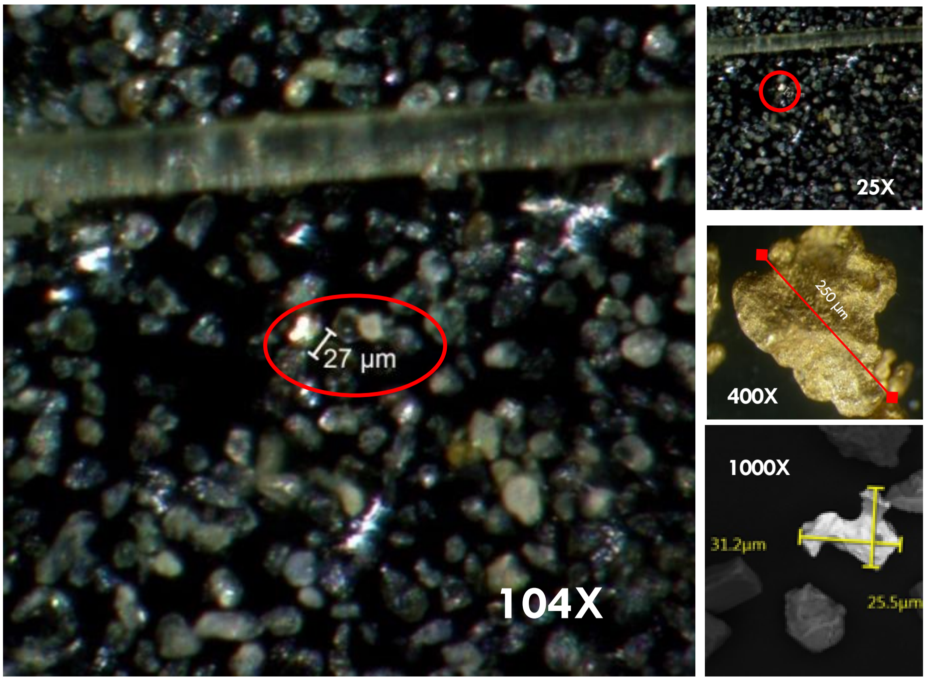
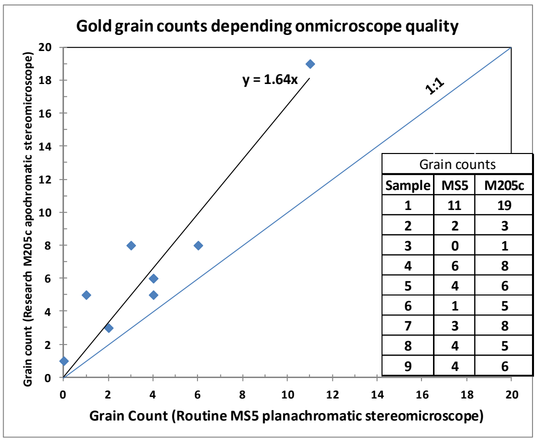


Figure 4. Examples of gold grains as seen at various magnifications with different types of microscope.
Left: 27 µm gold grain seen at 104x with a high-end apochromatic stereomicroscope (Leica M205-c, annular illumination). The blurred horizontal bar is a human hair. Tests indicates that sorting with

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

such stereomicroscope increase gold grain counts by about 57% compared to usual stereomicroscopes.
Upper-right: Same field of view with a conventional plan-achromatic stereomicroscope (Leica MS-5, oblique illumination) at 25x. The 27 µm gold grain is barely recognizable although such equipment is in current usage in most laboratories.
Middle right: An example of a large 250 µm grain seen with a metallographic dark-field microscope at 400x (Wild M21). The limited depth of field does not enable proper focus of the edges despite the grain being a flat flake.
Lower-right: Back-scattered electron image of a complex 31 µm gold grain acquired with an automated SEM routine. Notice the depth of field and resolution of minute details enabling textural studies. Such image is acquired on every single grain by the automated routine. Scale bars were added manually.



Sample	MS5	M205c
1	11	19
2	2	3
3	0	1
4	6	8
5	4	6
6	1	5
7	3	8
8	4	5
9	4	6

Figure 5: Results of a test where the same series of concentrates were sorted for gold grain under a routine Leica MS5 stereomicroscope and a research grade Leica M205c stereomicroscope by experienced mineralogists.

Visual identification relies on the skills of the operator and day-to-day constancies may vary over time. The development of operator-independent procedures is thus essential to yield consistent results that can be compared through time.

Gold grain counting can be automated either on a motorized high magnification optical microscope or with a motorized scanning electron microscope (SEM). But still, any grains identified by optical method would require EDS analysis with an SEM to be confirmed.

Grains cannot be manipulated in the course of an automated scanning process, meaning they cannot be swept from a pile, and need to be spread as monolayer on a stable observation substratum. In such monolayer, large grains cannot be observed simultaneously to small ones, first because of limited depth of field that would put either large or small grains out of focus, second because small grains may be shadowed by larger ones. Consequently, the +50 µm size fraction of the superconcentrates are separated with disposable woven meshes in a custom-made glass sieves (figure 2). The +50 µm material is then sorted visually under an apochromatic stereomicroscope (Leica M205C) at a magnification up 104× by a trained mineralogist. The -50 µm fraction is dusted on a double-sided carbon tape stick on top of a 40 mm square aluminum plate (Figure 3b). Approximately 50 mg of the finer material (-50 µm) can be hold as monolayer, which represents in excess of 1 million grains. Plates are then mounted on a sample shuttle, and inserted into a numerically controlled SEM (either a 2013 Zeiss EVO MA-15-HD with a LaB_6 emitting source equipped with an Oxford Instrument X-Max 150 mm^2 EDS-SDD detector or a 2018 Zeiss Sigma 300 VP FEG equipped with Oxford Instrument Ultim-Max 170 mm^2 EDS-SDD detector). Analyses are performed under low nitrogen pressure of 40 Pa in the sample chamber to avoid outgazing of the substratum, but allowing the drainage of the electrons.

 doi:10.20944/preprints202102.0186.v1

The SEM routine, which has some similarities with the precious metal routine of a MLA (Mineral Liberation Analyzer; e.g., [66]), is implemented on Oxford Instruments' Aztec-Feature (ver. 4.2). As the routine is operated on dusted material, rather than on polished epoxide mount, it enables scanning of the entire superconcentrate, and not only the fraction that is exposed by polishing. The routine acquires a backscattered electron (BSE) mosaic of 520 to 560 images of 1.92 x 1.44 mm (1024 x 768 pixels, resolution of 1.88 µm/pixel) of each sample (Figure 4a). The BSE brightness and contrast are adjusted so particles with a density >5 g/cm^3 are discriminated. This density is used to avoid detecting monazite, which mineral is ubiquitous (thousands) in the HMC, and hinders the length of the acquisition. Using a density lower than pure gold (i.e. 17 g/cm^3) allows detection of gold grains even if they are shadowed or have irregular surfaces. Clusters of bright pixels are then segmented into individual particles and the EDS acquire an X-ray spectrum that is deconvoluted into a qualitative chemical analysis. The mineral specie is identified in real time with a classification tree, highlighted in false color on the mosaic. Upon completion of the automation, a high resolution (image dimensions of 144 x 108 µm, 0.14 µm/pixel) is acquired of each gold grain, and a semi-quantitative EDS spot analysis is prompted. Size and detailed morphological characteristics (long and short axis, axis ratio, equivalent circle diameter, and area) are measured. All the information is then compiled and presented in a report. Figure 3d shows a mosaic of gold grain images from a single till sample as automatically generated by the system. The automated routine has the benefit of not being labor intensive, running overnight without attendance, and not relying on the operator's skills or day-to-day conditions.

Optical pre-sorting of gold grain can be inserted the procedure in order to reduce SEM time. The distinctive yellow color of gold is due to its quite distinctive reflectance spectrum, which is highly reflective from red to green, but poor for blue wavelength [67, 68]. This means that such spectral signature can be recognized with a standard RGB camera, and pixels with such signature can be readily detected by subtracting the signal of blue pixels from red pixels. However, the technique, based on three wavelengths only, is not sensitive enough to discriminate efficiently gold from other yellow minerals, such as sulphides, monazite, some garnets, brass, etc. Furthermore, at high magnification, fringes of yellow chromatic aberrations may rim the grains, which confuses the system. Therefore, gold grains cannot be detected on sole premise of their distinctive color. A single sample would generate tens of thousands of such yellow grains, or false positives The issue is circumvented by reprocessing the segmented images of yellowish grains with a trained dataset of confirmed gold based on deep convoluted neural network (Inception V4 architecture) [71, 69, 70]. By properly training the system, the false positive rate can be reduced to a few tens per samples. In practice, the superconcentrates are mounted as for the SEM scanning, and placed onto a sample shuttle clipped to a motorized microscope stage (Zeiss AxioZoom V16 equipped with Episcopal LED ring light, a PlanNeofluar 2.3x objective and a Zeiss AxioCam 506color digital camera) operated at 63x. A mosaic of image covering the sample with a resolution of 1.2 µm and a depth of field of 28 µm is assembled in image processing software (Zeiss Zen 2.5 Pro). Images of the grains are extracted, along with their coordinates, and processed with the CNN (ARTPhot) routine. Then, the sample shuttle is moved into the SEM, and possible gold grains coordinates are transferred. Grains are then brought one by one under the SEM hyperconical lens where high magnification BSE image and EDS spectrum are acquired to confirm the grains.

Optical presorting has the benefits of being fast and cost effective. Test conducted in autumn 2018 indicated that in excess of 95% of the gold grains detected by SEM scanning were also detected by visual sorting (ie: 5% false negative rate), a performance that improves through time with retraining of the AI routine. Again, while detection rate is near complete with gold grain larger than 25 µm, it falls to about 50% in the 5-10 µm size range. Contrarily to EDS scanning, optical sorting as currently available does not enable detection of other meaningful minerals.

2.3 Recovery measurements

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

Measuring accurately the weight recovery of gold by gravimetric method is achieved simply by assaying and mass balancing the feed, the concentrate and the tails. Inversely, measuring recovery in term of grain abundance is difficult, since the initial abundance of grain in the feed cannot be measured without sorting them. Gold grains being too small to be efficiently manipulated, it is complicated to manufacture a synthetic reference sample with pre-established number of grains [72] unless only large grains are used, which are notoriously easy to recovery and thereof introducing a bias. The issue can be circumvented by reprocessing the tails. Through successive reprocessing, the tails of a sample will be the feed of its successor, and the number of recovered grains will decrease according to the recovery rate which is then a convergent factorial series. Recovery is then calculated as

$$R=1-N_2/N_1$$

Nx being the number of grains recovered on a specific concentration cycle.

Recovery can be calculated separately for various grain size interval, shape, composition or else. Tests are routinely conducted by reprocessing the sample's tails as part of the QAQC program. A recovery curve according to grain size is calculated, suggesting a recovery in excess of 90% for grains larger than 80 µm, with a progressive decrease with grain size, and recovery collapse around 20-25 µm (figure 6). The recovery rate is dominantly influenced by the concentration process, since identification rate with the SEM is in excess of 95% down to a few micrometres.

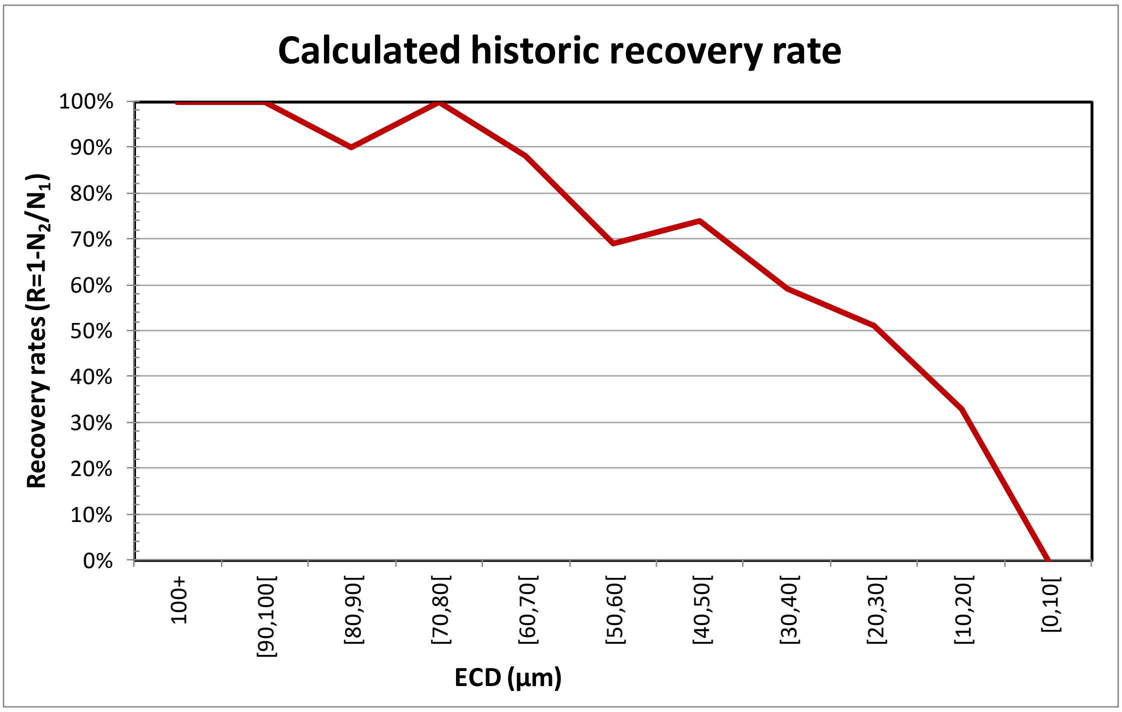


Figure 6: Typical recovery rates of gold grain with the fluidized bed according grain size, as obtained from 2018 testing. A recovery collapse is noted for grains smaller than 20 µm, which fades almost to zero below 10 µm. Despite all precautions taken by the laboratory, the recovery curve fluctuates through time and the procedure still requires constant QAQC monitoring.

3. Results

To illustrate the effectiveness of the improved method, we compare recent surveys conducted over the same area using both the conventional and improved methods. The results includes counts and sizes of gold grains recovered from till samples collected in a ca. 250 km² area surrounding the Borden gold deposit (Ontario, Canada). A first series of regional samples were collected by Ontario Geological Survey and Probes Mines between 2011 and 2014 and processed by the same laboratory using the conventional method. To calibrate the survey, a

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

series of samples were also collected by Probe down-ice of their Borden gold deposit in 2014. The second series of sample, collected between 2015 and 2017 on behalf of Goldcorp Canada, includes regional surveys that partly encompassed Probe surveys, plus a replicate of Probe samples down-ice of the Borden gold deposit. Follow-up sampling down-ice of anomalies and samples collected by subsequent Sonic overburden drilling has been excluded. Sampling procedures and sample size and quality are assumed similar, with the exception that 2014 samples were sifted in the field while others were sifted in laboratory conditions. The locations, survey type, and gold grain counts from the conventional and improved methods are listed in Tables 1. The sizes (width and length) of gold grains recovered by the conventional and improved methods are discussed in the companion paper [36] while their chemistry is discussed in a second companion paper [37]. Results will be discussed solely in regard of method efficiency, and no details pertaining to mineral exploration are here to be disclosed.

Survey	Type	Year	Method	Samples	Total (grains)	Average (GG / s)	Nor. Avg. (GG / 10 kg)	Maximum (grains)
OGS	Regional	2011	Conv.	69	78	1.13	1.41	10
Probe Minerals	Regional	2012, 2014	Conv.	724	582	0.80	1.00	10
Probe	Borden	2014	Conv.	40	487	12.17	15.21	41
Goldcorp	Regional	2015, 2016, 2017	ARTGold	985	9119	9.26	10.64	310
Goldcorp	Borden	2016	ARTGold	61	6647	105.69	116.2	507

Table 1: Statistics on the gold grain counts from the various surveys used in the current study.

3.1. Study area

The Borden gold deposit is located 160 km south-west of Timmins, in the Wawa Subprovince of the Archean Superior Province. The gold deposit occurs in the west trending Borden Lake greenstone belt, in the southern portion of the Kapuskasing Structural Zone [73-76]. The Borden Lake greenstone belt, which has undergone high-grade metamorphism (up to granulite facies), consists of mafic to ultramafic gneisses, pillow basalts, felsic meta-volcanic rocks, felsic porphyries, and tonalites that are overlain by a >30 m thick suite of Timiskaming-aged clastic metasedimentary rocks [77-80]. The gold mineralization, initially identified in outcrops by Probe Mines, essentially occurs in a ductile shear zone within the volcano-sedimentary horizon. It consists of a high-grade core with gold associated predominantly with quartz flooding/veining and potassic alteration, and a low-grade envelope with gold associated with disseminated and fracture-controlled pyrite/pyrrhotite with local silicification [81, 82]. In 2015, the deposit was acquired by Goldcorp Canada Inc. (currently Newmont-Goldcorp Corporation), and commercial production was inaugurated in September 2019 [83].

The study area has been eroded by the Wisconsinan glacial advance, which left the bedrock partly covered by Wisconsinan glacial sediment (Figures 7 and 8). The detailed surficial geology is reported in Gao [84] and Girard and Villeneuve [85]. Kilometre-sized patches of thick and continuous till are restricted to the northern and south-eastern portions of the study area, whereas thin discontinuous veneers of till occur mainly in the eastern and western portions. The till consists of poorly sorted silty sand or sandy diamicton with pebbles. The study area also contains glaciofluvial and glaciolacustrine material deposited during the withdrawal of the late Wisconsinan ice-sheet, sampling of which has been avoided. The regional ice-flow direction is oriented south–south-west as indicated by glacial landforms (e.g., drumlins, flutings, crag and tail) and striations engraved on the bedrock. This ice-flow dispersion does not seem to have reworked former dispersion or to have been remobilized by subsequent sedimentary events.

 doi:10.20944/preprints202102.0186.v1

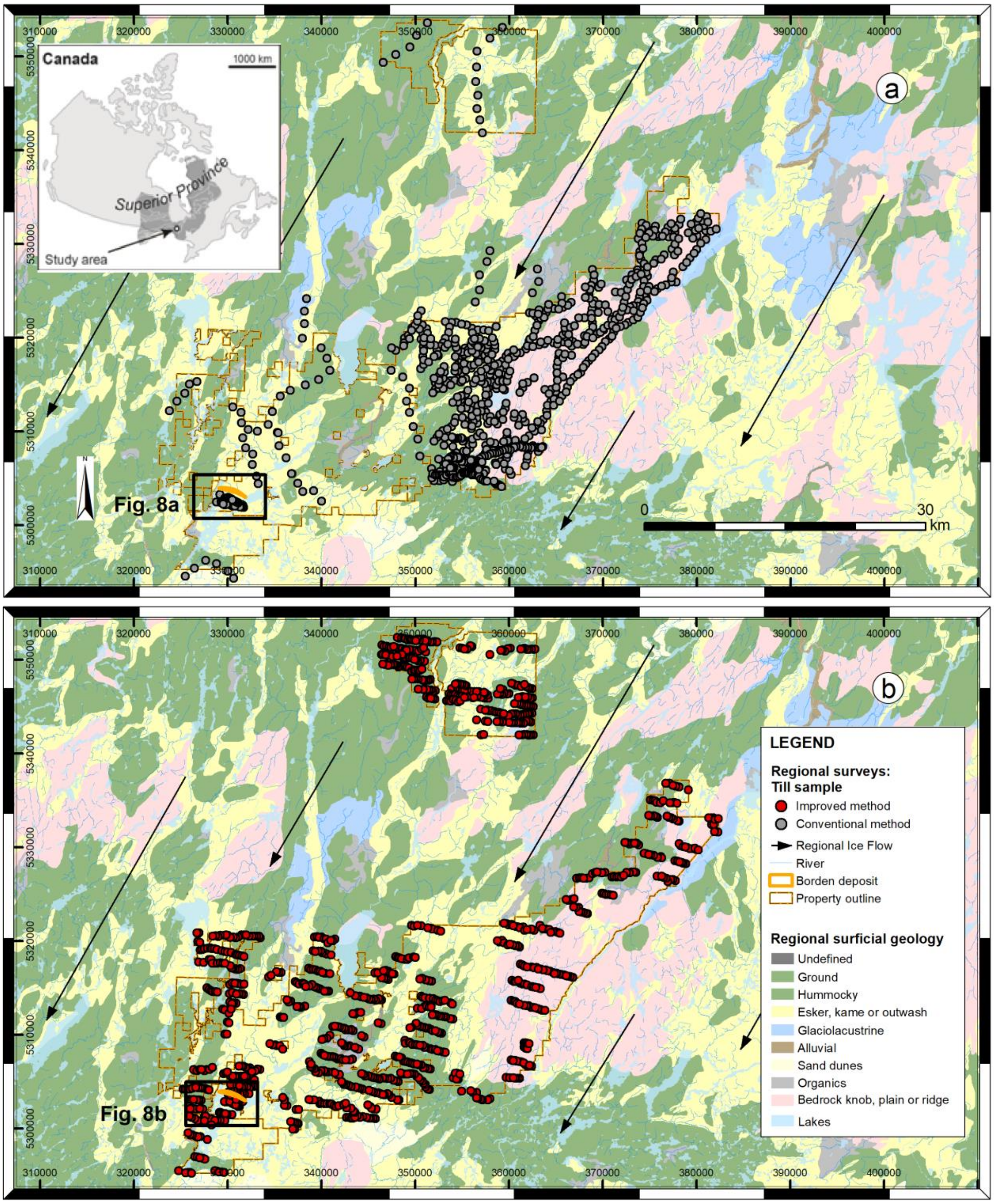


Figure 7. Map of the regional area surrounding the Borden gold deposit showing surficial geology and locations of till samples processed with the conventional method (a) and the improved method (b). Note the number of samples for the conventional method n = 833 and for the improved method n = 1192.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

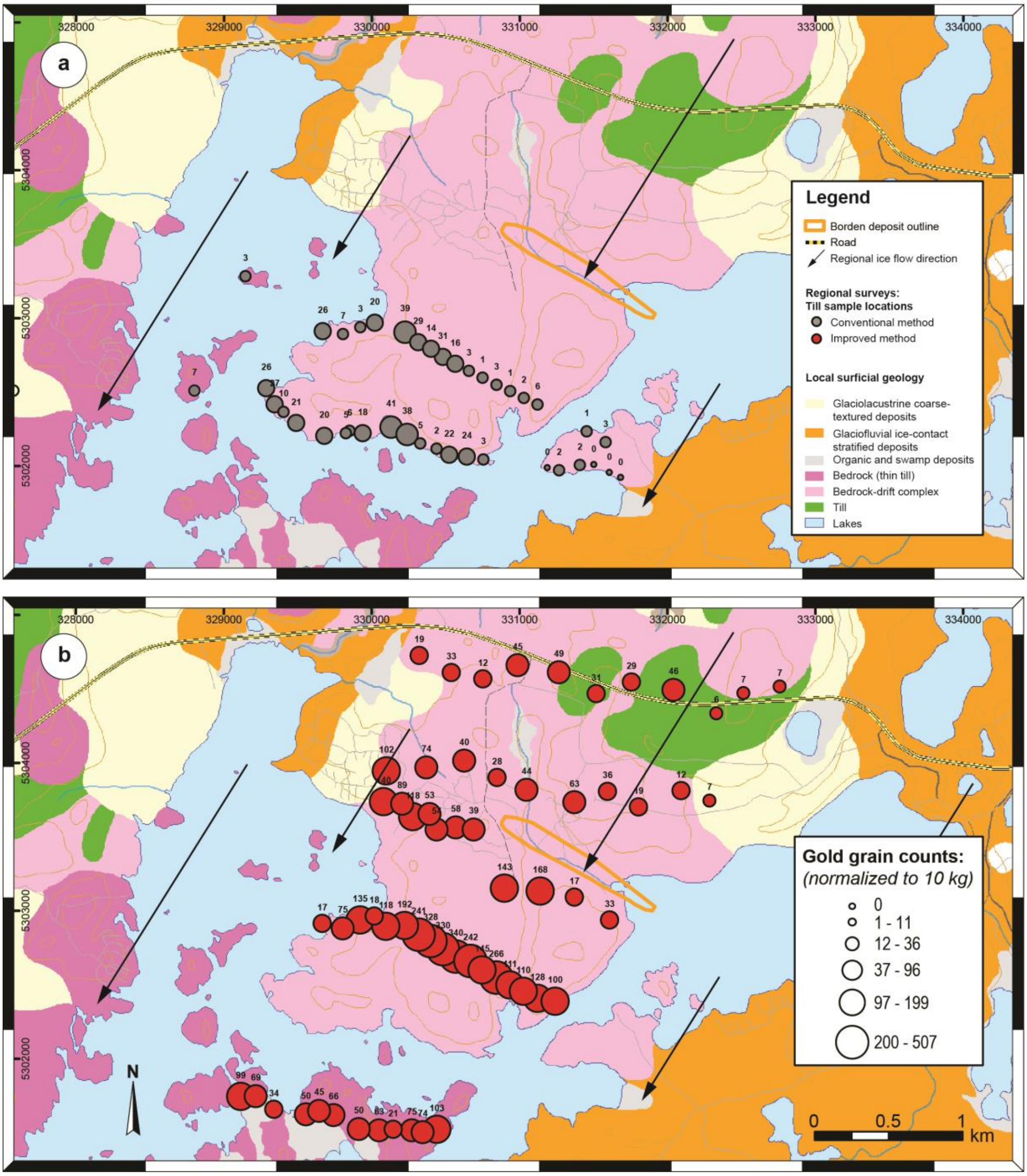


Figure 8. Map of the local area surrounding the Borden gold deposit showing surficial geology and locations of till samples (orientation surveys) processed with the conventional method (a) and the improved method (b). Note the number of samples for the conventional n = 40 and for the improved method n = 61. The bubble diameter refers to the gold grain count normalized to a 10 kg sample. On the main profile down-ice of the deposit, samples for the improved method were collected in the same location within GPS accuracy from the previous conventional survey and can be considered as paired samples.

3.2. Till surveys

Till samples were collected with hand shovels with the same protocol during regional and orientation surveys. The orientation till survey, commissioned by Probe Mines prior to their regional survey in 2014, aimed at characterizing the footprint of their discovery before initiating the regional surveys. A total of 40 samples were collected along 2 profiles located respectively 1 and 1.5 km down-ice of the outcropping mineralization (Figure 8). The survey did not extend southward due to the presence of the Borden Lake coinciding with the property boundaries. The samples were processed with the conventional method and results indicate a dispersion train about twice the width of the outcropping occurrence, with a maximum count of 41 gold grains in a sample collected 1.5 km down-ice. This contrasts with the results for the 793 samples from regional surveys, either by Ontario Geological Survey (OGS, 2011, 69 samples; [84]) or Probe in 2012 and 2014 that yielded a total of 660 grains [no report available], for an average count of 0.83 gold grains per sample using the conventional method.

After its acquisition of the Borden property from Probe Mines, Goldcorp commissioned a series of surveys between 2015 and 2017 [86, 87, 88, 89]. A regional till survey, using sample spacing similar to the Probe Mines' regional survey, was conducted to cover previously sparsely sampled areas. A total of 985 regional samples were collected and processed with the currently described method, yielding an average count of 9.3 grains per samples. In addition, an orientation survey was conducted to assess the extent of the mineralization footprint, for 61 samples collected along 6 profiles located from 2 km up-ice to 3 km down-ice of the mineralization. The profile located 1 km down ice of the mineralization replicated the one from the Probe Mines, collecting the samples at the exact same sites (within GPS accuracy) and therefore generating 15 duplicates. Maximum counts, normalized to 10 kg samples, down-ice of the mineralization are of 185 gold grains at 200 m, 479 gold grains at 1 km (compared to the maximum count of 39 of the Probe survey along the same profile), 118 grains at 2 km, 70 grains at 4 km, and 30 grains at 6 km and counts below 30 grains further away. Such pattern is typical of glacial dispersion trains rooted directly on a mineralized occurrence.

3.3. Gold Grain Counts

For the collected till samples, gold grain counts using the standard and new methods differed markedly. Overall (regional plus orientation surveys), the conventional method recovered 1,147 gold grains from 833 till samples (~ 6,436 kg of -2 mm material, assuming 8 kg per samples) for an average of 0.178 grains per kilogram. By comparison, the improved method recovered 15,566 gold grains from 1046 till samples (~ 11,873 kg, or 8252 kg <1mm) for an average of 1.68 grains per kilogram. Thus, the improved method recovered 9.43× more gold grains per kilograms of sifted material relative to the conventional method. This leads to significant differences in the count distribution (Figure 9). The conventional method failed to recover any gold grain in 423 samples (50.8%), whereas the improved method recovered gold grains in all but 18 samples (i.e., 1.65% of samples were deemed barren). Similarly, for the regional survey, the conventional method yielded only four samples with an excess of 6 grains, for a maximum count of 10, meaning that nearly all samples had counts lower than the average of the new method. Similar ratios (7-10x) between counts from both methods were obtained in various proficiency tests preliminary to other projects.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

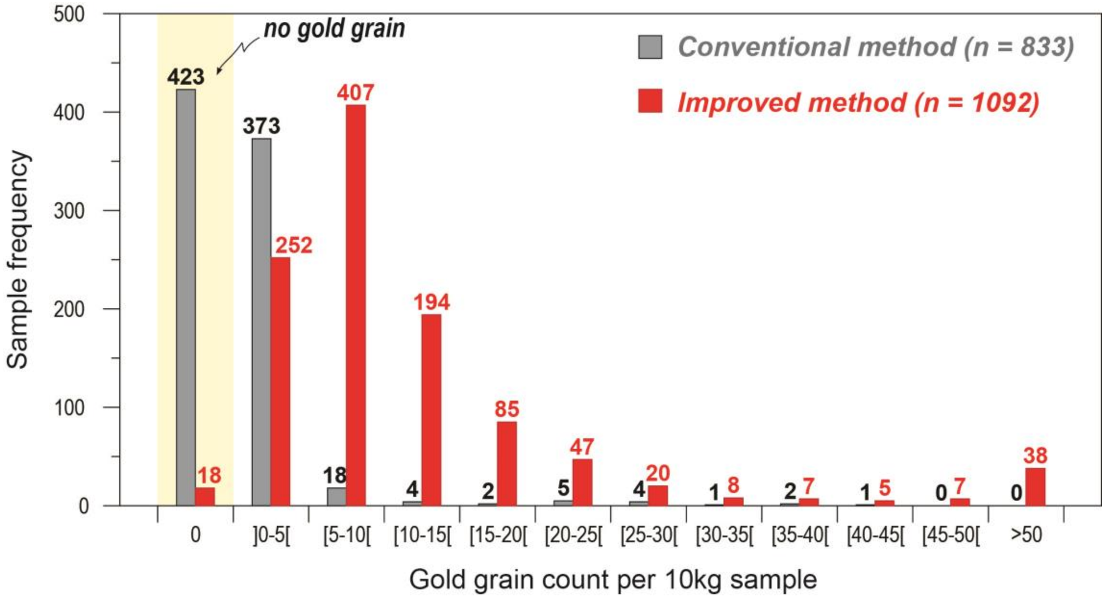


Figure 9. Comparison of the gold grain count per sample (normalized to 10 kg) obtained for the conventional and improved methods from till surrounding the Borden gold deposit.

3.4. Gold Grain Sizes

Since recovery of grains larger than 100 µm is considered efficient with the conventional method, increase in grain counts shall be dominantly from small grains assuming a constant sample weight. While the automated SEM method generates accurate measurement of grain dimensions, the conventional method only provides visual estimates typically disclosed as 25 µm increments. To compare results, abundance of grains with SEM measurements were pooled using the size interval as reported for the conventional method, with samples normalized to 10 kg and sieved at 1 mm (figure 9). Given the large differences in abundance between samples from orientation and regional survey, results are presented separately. For the conventional method, regional samples (n = 793) represented 6,145.54 kg of material while orientation samples (n = 40) comprised 290.6 kg for 660 and 487 gold grains respectively. For the SEM-based method, regional samples (n = 985) represented 11,122 kg of material and the remaining orientation samples (n = 61) represented 751 kg of material, for 9,119 and 6,447 gold grains respectively.

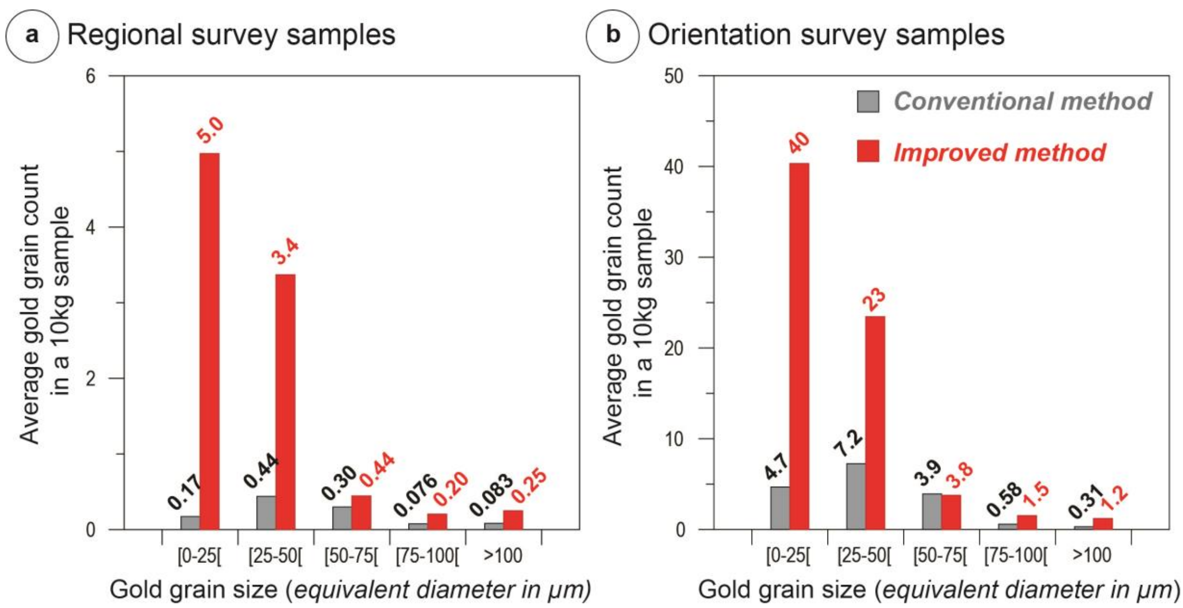
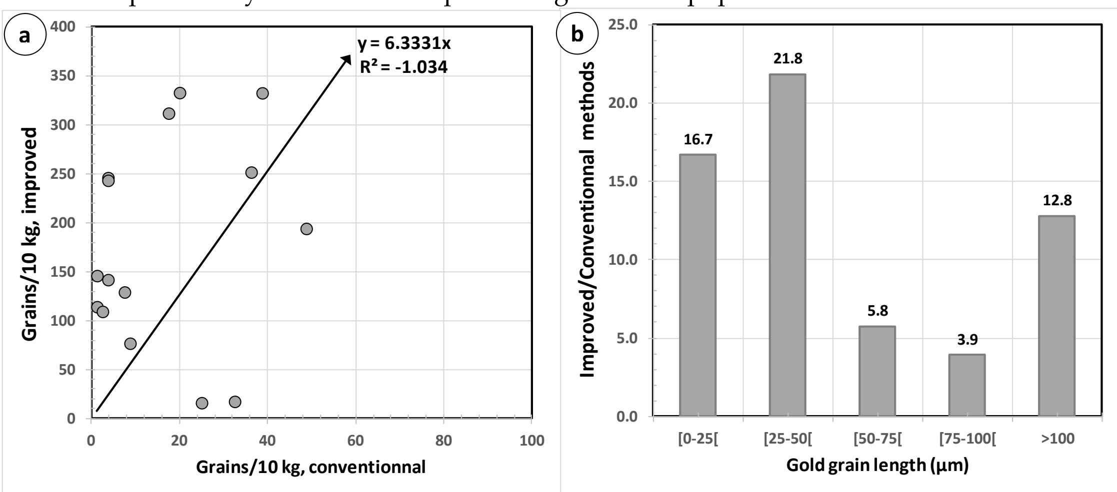


Figure 9. Comparison of the size distribution of the average gold grain count in a 10 kg (-1 mm) sample for the conventional and improved methods. Gold grain size distribution of (**a**) regional till samples and (**b**) orientation till samples collected around the Borden gold deposit. See text for further details. Note that the vertical scale for orientation samples (b) is 8.3× the vertical scale of the regional samples (a).

In the regional samples, the improved method recovered 28.6× and 7.67× more gold grains than the conventional method for the [0–25[µm and [25–50[µm size ranges, respectively (Figure 9a). For the [50–75[µm, [75–100[µm, and >100 µm size ranges, the improved method recovered 1.48×, 2.67×, and 3.02× more gold grains relative to the conventional method, respectively (Figure 9a). In orientation samples, the improved method recovered 8.61× and 3.23× more gold grains than the conventional method for the [0–25[µm and [25–50[µm size ranges, respectively (Figure 9b). However, for the [50–75[µm size range the conventional method recovered 1.04× more gold grains than the improved method (Figure 9b), indicating approximately the same recovery rate for both methods. For the [75–100[µm and >100 µm size ranges, the improved method recovered 2.63× and 3.90× more gold grains relative to the conventional method but the small number of counts render comparison fallacious (figure 9b). Thus, the improved method recovered generally more gold grains than the conventional method across the range of grain sizes for both regional and orientation samples. More importantly, as gold grain size decreases, the difference in performance between the two methods increases; the improved method being far more efficient at recovering fine gold grains (<25 µm), especially from regional samples.

3.5. Paired Samples

To confirm that observed differences for gold grain counts and sizing between the two methods are not related to till heterogeneity the results from 15 paired samples collected 1.5 km down-ice of the Borden gold deposit were compared (Figure 10; Table S5). Counts in these samples are elevated (up to 48 for the conventional method and up to 340 for the improved method, both normalized to 10 kg) enabling statistical comparison. Aside of two pairs of samples, the improved method recovered 5×–100× more gold grains per samples than the conventional method (Figure 10a). A total of 201 gold grains were detected by the conventional method (i.e., 17 grains per 10 kg of material), whereas the improved method yielded a total of 3356 gold grains (226 grains per 10 kg of material). This observation indicates that along the profile of paired samples, the improved method recovered 13.4× more gold grains per weight of material. Results also show differences for the various size fractions. The improved method recovered 16.7×, 21.8×, 5.8×, 3.8×, and 12.8× more gold grains than the conventional method for the [0–25[µm, [25–50[µm, [50–75[µm, [75–100[µm, and >100 µm size ranges, respectively (Figure 10b). Difference in counts between both methods is stark, and a paired Student test indicates a probability of 1.6×10^{-5} of representing the same population.



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

Figure 10. (**a**) Comparison of gold grain counts per samples between the conventional and improved methods for 15 paired samples; (**b**) Comparison of the ratio of the number of grains per 10 kg for the improved versus the conventional methods, according to grain size brackets.

3.6. Benefit of improving the counts

If gold grains are scattered in a homogeneous medium (a till in a specific sampling site), the probabilities of occurring in an aliquot (sample) follows a Poisson distribution (or binomial distribution if using a limited number of aliquots). Hence, the probability of having a certain grain in a sample equals the probability of having any other grains in the same sample [76, 90] and is equal to the probability of having this specific grain in another aliquot. This means that the number of grains present in a set of samples taken from a homogeneous site will differ from samples to samples in a predictable manner according to the mass function. Assuming an average number of grain per sample (expectancy; λ, which, in a Poisson distribution, is equal to the variance), the distribution will have a standard deviation of $\sqrt{\lambda}$ and a variation coefficient of $1/\sqrt{\lambda}$. This means that smaller is the average number of grain in a sample, higher would be the variability of the counts in the sample. Thus, for an average of 1 grains per sample, as seen in many regional surveys, the standard deviation would be of 1, equal to the average count. Then, 36.8% of samples would be barren and samples having 6 grains or more would occurs in 1 out of 1000 samples without necessitating contribution of a local secondary source (mineral occurrence) and being considered anomalous.

On a regional scale, the till blanket is not necessarily homogeneous, having contribution mixture from distant as well as a multitude of local source. Thus, the expectancy of each sample is different, and the distribution of such expectancies would follow a distribution that is superposed onto the intrinsic variation induced by the Poisson mass function on each individual sample. The variance of such system is then equal to the sum of the variance of each probability function affecting the system. This increases the variance in the gold grain abundance among sample, thus increasing the odds of having barren samples as well as elevated counts.

The regional population as measured with the conventional method yielded an average of 0.83 grains per samples, with a standard deviation of 1.24 grains and a variation coefficient of 1.5. Assuming a Poisson distribution, it means that 43.6% of the samples shall be barren, and 99% of the samples shall have 3 or less grains. According to the Poisson mass function, a count of 5 or more grains has a probability of 0.14%, or a single sample across the survey, while it was obtained in 14 samples. Such skewed distribution compared to a true Poisson distribution is induced by the till heterogeneity on the regional scale, or simply by the presence of anomalous samples tapping a local gold occurrence. Thus, a 5 grain count can be used as anomaly threshold.

Increasing the average number of grains decrease the intrinsic variation coefficient according to a square-root function. The improved method has an average of 9.26 grains with a standard deviation of ±11.98 gains and a variation coefficient of 1.29. This, compared to the results from the conventional method, suggests an increase in average counts by 11.2x, which means a decrease of the intrinsic variation coefficient by 2.7x. Highest expectancy (42.8%) would be for sample with 6 to 8 grains per 10 kilograms, while only one sample from the entire survey is expected to be barren. Inversely, a sample with 17 or more counts are twice or more too abundant, and thus have more than 50% chance of being anomalous. Such count can thus be used as anomaly threshold.

The purpose of improving an analytical method is, from an exploration standpoint, to improve the sensitivity of the survey (i.e. signal to noise ratio). Obtaining higher counts would be of lesser meaning if all counts increase proportionally without reducing their variance. Results from the anomalous duplicate samples indicate a significant improvement in the method sensitivity (Figure 9) and its capability to enhance feeble signal. A signal to noise ratio (S/N) is computed by dividing the gold grain counts of anomalous samples by the anomaly

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 February 2021 doi:10.20944/preprints202102.0186.v1

threshold obtained from the regional survey. Results along the test profile indicate that the mean S/N ratio of the conventional method is of 2.7x, with 9 samples above the anomaly threshold. In comparison, the improved method yielded an average S/N ratio of 13.1x, or four time more contrasted than the conventional method. Furthermore, none of the samples tested below the anomaly threshold.

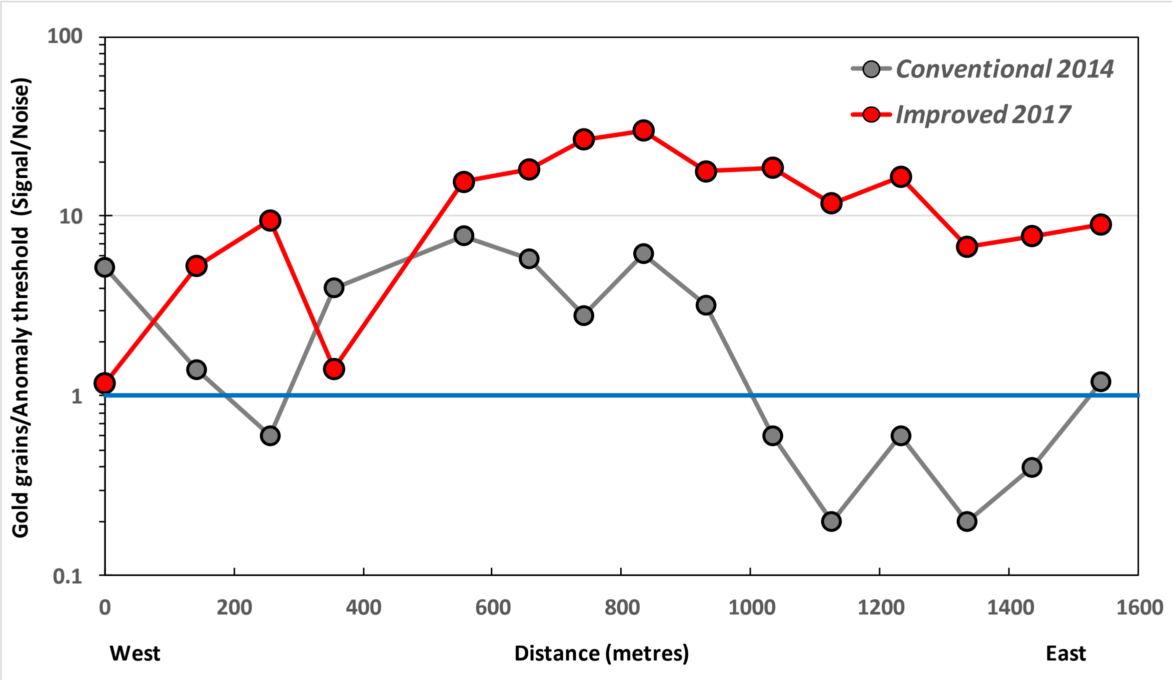


Figure 9. Comparison of gold grain counts normalized to the anomaly threshold for the conventional and improved methods along the profile of the 15 paired samples. Notice the logarithmic vertical scale, while the horizontal scale represents the distance away from the westernmost sample.

Mineral deposits are defined as the envelope within which a metal is enriched above a certain grade that has the potential of being economically mined. These are typically surrounded by haloes of lower grade rocks that vanish into the barren host rock. These halos, where associated with alteration system, can be significantly larger than the deposit itself. Exploration methods that are sensitive enough shall be capable to detect the signature of such halo, and not only the deposit itself. Thus, the footprint of the deposit is expected to be larger than the deposit itself, as shall be the gold grain dispersion train in the glacial sediments. On the duplicated profile, the anomaly detected by the automated method encompasses 14 contiguous samples, for a minimal width of 1,500 metres, and remain open to the east. By comparison, only 6 contiguous samples plus one erratic are exceeding the background signal, for a maximum contiguous width of 700 metres. The improved method can then detect the anomalous signal over at the least twice the width than the conventional method, expanding the detectable footprint accordingly. Similarly, the detectable dispersion is detected over much longer distance with the improved method, although it is not accurately documented. The signal from the low-grade halos is distinctively detected as seen from sample collected up-ice of the deposit (figure 7).

From an exploration standpoint, increasing the grain counts have three direct benefits: First, being capable to detect dim signals of a broad dispersion train allows reduction of the sampling density. Typically, regional sampling is conducted along fence every 1 to 5 kilometres, depending on ice dynamic, with sample distance along a fence of approximately the third of the width of the expected source rock, usually in a quincunxes pattern. Widening of the detectable source thus lead to reduced sampling density along the fences. The breadth of the anomaly along the duplicated profile with the improved method thus signifies that half the samples would have been enough to detect the deposit in the course of a regional survey, compared to the conventional methods. The same way, line spacing can also be increased, further reducing the required number of samples. Inversely, in the case where the source is smaller than the sampling interval, increasing the sensitivity broadens such source, and thus increases the odds of detecting its dispersion. In both cases, it represents either an overall cost reduction of the survey or an improvement of discovering odds.

Second, reducing the intrinsic variance of the counts on a specific sample means that the counts are more reliable. Thus, elevated count has better odds of being a true anomaly. In a low counts conventional survey, a mildly elevated count (e.g. 5 grains in the current survey) will not be discriminating compared to the tail of a Poisson distribution from the regional signal. This is usually circumvented by requiring the contiguity of two such mildly elevated counts to consider the samples as real anomalies. By improving the signal to noise ratio, either by intrinsic variance reduction or by removing false gold grains, discrimination of a true anomaly related to a local source compared to a false anomaly from the background becomes more robust. Thus the contiguity requirement can be eliminated in most cases.

Third, increasing the number of grain detected by kilograms of sample means that lesser material is required to achieve representativeness. Till sampling is expensive, especially in logistically complex or remote areas. Reducing sample weight, from usual 10-20 kg to 3-5 kg per sample, diminishes sampling and shipping costs, and significantly reduces the hardship and risk of injuries for samplers. Similarly, when sampling is conducted by drilling (reverse circulation, sonic, split-spoon, triple tubes, etc), wide tube caliber (PQ or 12.2 centimetres) is typically required to recover 10 kilogram of material per metres. Decreasing sample size means that either shorter interval can be sampled, or smaller drilling caliber can be used. This can lead to dramatic cost reduction, since smaller drill rig may be sufficient. With the use of a more sophisticated method enabling the recovery of sub-micrometre gold grain currently under development, statistical representativeness was achieved with a 300 grams sample that can be collected with a BQ (6 cm) diameter split-spoon driven with a hand-portable pneumatic hammer.

4. Conclusions

The methods developed for recovering and counting gold grains in glacial till are recognized as the prime tool for regional gold exploration under glaciated cover being the sole method enabling detection of distant signal. The new method (referred as "ARTGold™") presents significant improvements relative to the conventional method.

1. Gold grains in ore deposits and till are mostly fine-grained. Despite numerous successes, the conventional method for recovering gold from till does not provide optimal results as gold grains <50 μm are poorly recovered and identified.
2. The proposed improved method is based on an optimized recovery procedure that concentrates fine gold more effectively, and an automated SEM routine that reliably detect and count all recovered gold grains, independent of the operator skill and surrounding conditions.
3. From till samples collected on a regional survey near the Borden gold deposit (Ontario, Canada), the conventional method recovered an average of 1.04 gold grains per 10 kilograms (-1 mm) sample, whereas the improved method recovered 10.63 grains per 10 kilograms (-1 mm) samples. Grain abundance in a sample being dictated by a Poisson distribution law, it means that the intrinsic standard deviation on the count grows as a square-root of the count, meaning that higher are the counts, lower is the variability and better is the reliance on the results. This significant difference is due to the improved method being better at recovering minute gold grains.
4. A 15 samples profile has been duplicated about 1 kilometre down-ice from the Borden gold deposit. Samples processed with the improved method yielded an average signal

to background ratio of 13.1x, with all but 1 sample being distinctively anomalous. This compare advantageously with the conventional method which had an average signal to background ratio of 2.7x, and anomalous signal being detected in only 8 of the 15 samples.

5. With the perspective of a regional exploration program, the improved method allows an overall cost reduction of the program by enabling wider sampling pattern, more dependable results on which decision are taken, and sample weight reduction leading to safety improvement for the samplers.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, ….to be confirmed

Author Contributions: Conceptualization, Réjean Girard; Data curation, Jonathan Trembaly and Alexandre Néron; Formal analysis, Réjean Girard; Methodology, Réjean Girard; Software, Jonathan Trembaly and Alexandre Néron; Validation, Jonathan Trembaly; Writing – original draft, Réjean Girard; Writing – review & editing, Hugues Longuépée.

Funding: This study was part of larger project funded by a Québec Fonds de Recherche Nature et Technologies (FRQ-NT) grant to L.Paul Bédard, which subsidized C Duran work, with contributions from IOS Servives Géoscientifiques Inc (Projet de recherche orienté en partenariat; Grant number: 2015-MI-191750).

Acknowledgments: Goldcorp Corporation is acknowledged for granting permission to initially publish the data acquired on their property (June 2018). L.Paul Bédard (UQAC) and Charley Duran (UQAC) are thanked for their contribution into the writing of a preliminary version (2018) of the manuscript. Sheida Makvandi, Phillipe Pagé, Patrice Villeneuve, Natacha Fournier, Karen Gagné, Mélanie Aubin and Karine Desbiens (IOS Services Géoscientifiques Inc.) are thanked for their valuable assistance with SEM operation, quaternary geology, database management, quality control, drawing and editing respectively. D.H.C. Wilton (MUN) and G. Thompson (CNA) are also thanked for invitation to contribute to this special issue and for editorial handling. Anonymous reviewers are thanked for their constructive comments that improved the manuscript considerably.

Conflicts of Interest: The authors being respectively general manager, SEM operator, research scientist and senior scientist with IOS Services Géoscientifiques Inc., they participated in the development of the analytical procedure assessed in this study, which procedure is commercially offered by the corporation. Newmont-Goldcorp Corporation and FRQ-NT had no role in the design of the study, the analysis, or interpretation of data, in the writing of the manuscript, nor in the decision to publish the results.

References

1. McClenaghan, M.B.; Cabri, L.J. Review of gold and platinum group element (PGE) indicator minerals methods for surficial sediment sampling. *Geochem.: Explor., Environ., Anal.* **2011**, *11*, 251–263, https://doi.org/10.1144/1467-7873/10-IM-026.
2. Averill, S.A. Regional variations in the gold content of till in Canada. In Prospecting in Areas of Glaciated Terrain; MacDonald, D.R., Mills, K.A., Eds; Canadian Institute of Mining and Metallurgy, **1988**, 271–284.
3. Shelp, S.G.; Nichol, I. Distribution and dispersion of gold in glacial till associated with gold mineralization in the Canadian Shield. *J. Geochem. Explor.* **1987**, *27*, 315–336, https://doi.org/10.1016/0375-6742(87)90055-0.
4. Grant, A.H.; Lavin, O.P.; Nichol, I. The morphology and chemistry of transported gold grains as an exploration tool. *J. Geochem. Explor.* **1991**, *40*, 73–94, https://doi.org/10.1016/0375-6742(91)90032-P.
5. Hooke, R.LeB.; Cummings, D.I.; Lesemann, J-E.; Sharpe, D.R. Genesis of dispersal plumes in till. *Can. J. Earth Sci.* **2013**, *50*, 847–855.
6. Sauerbrei, J.A.; Pattison, E.F.; Averill, S.A. Till sampling in the Casa-Berardi gold area, Quebec: A case history in orientation and discovery. *J. Geochem. Explor.* **1987**, *28*, 297–394, https://doi.org/10.1016/0375-6742(87)90054-9.
7. Averill, S.A. Discovery and delineation of the Rainy River gold deposit using glacially dispersed gold grains sampled by deep overburden drilling: A 20-year odyssey. In New Frontiers for Exploration in Glaciated Terrain; Paulen, R.C., McClenaghan, M.B., Eds; Geological Survey of Canada, Open File 7374, 2017, 37–46.

8. Averill, S.A. The application of heavy indicator mineralogy in mineral exploration, with emphasis on base metal indicators in glaciated metamorphic and plutonic terrain. In Drift Exploration in Glaciated Terrain; McClenaghan, M.B., Bobrowsky, P.T., Hall, G.E.M., Cook, S.J., Eds.; *Geol. Soc. London, Spec. Publ.* 2001, 185, 69–81, https://doi.org/10.1144/GSL.SP.2001.185.01.04.
9. McClenaghan, M.B.; Peter, J.M. Till geochemical signatures of volcanogenic massive sulphide deposits: an overview of Canadian examples. *Geochem.: Explor., Environ., Anal.* **2016**, *16*, 27–47, https://doi.org/10.1144/geochem2014-315.
10. Plouffe, A.; Ferbey, T.; Hashmi, S.; Ward, B.C. Till geochemistry and mineralogy: Vectoring towards Cu porphyry deposits in British Columbia, Canada. *Geochem.: Explor., Environ., Anal.* **2016**, *16*, 213–232, https://doi.org/10.1144/geochem2015-398.
11. McClenaghan, M.B.; Parkhill, M.A.; Pronk, A.G.; Sinclair, W.D. Indicator mineral and till geochemical signatures of the Mount Pleasant W-Mo-Bi and Sn-Zn-In deposits, New Brunswick, Canada. *J. Geochem. Explor.* **2017**, *172*, 151–166, https://doi.org/10.1016/j.gexplo.2016.10.004.
12. McClenaghan, M.B.; Paulen, R.G.; Oviatt, N.M. Geometry of indicator mineral and till geochemistry dispersal fans from the Pine Point Mississippi Valley-type Pb-Zn district, Northwest Territories, Canada. *J. Geochem. Explor.* **2018**, *190*, 69–86, https://doi.org/10.1016/j.gexplo.2018.02.004.
13. Duran, C.J.; Dubé-Loubert, H.; Pagé, P.; Barnes, S-J.; Roy, M.; Savard, D.; Cave, B.J.; Arguin, J-P.; Mansur, E.T. Applications of trace element chemistry of pyrite and chalcopyrite in glacial sediments to mineral exploration targeting: Example from the Churchill Province, northern Quebec, Canada. *J. Geochem. Explor.* **2019**, *196*, 105–130, https://doi.org/10.1016/j.gexplo.2018.10.006.
14. Griffin, W.L.; Ryan, C.G. Trace elements in indicator minerals: area selection and target evaluation in diamond exploration. *J. Geochem. Explor.* **1995**, *53*, 311–337, https://doi.org/10.1016/0375-6742(94)00015-4.
15. McClenaghan, M.B.; Kjarsgaard, B.A. Indicator mineral and geochemical methods for diamond exploration in glaciated terrain in Canada. In Drift Exploration in Glaciated Terrain; McClenaghan, M.B., Bobrowsky, P.T., Hall, G.E.M., Cook, S.J., Eds.; *Geol. Soc. London, Spec. Publ.* **2001**, 185, 83–123, https://doi.org/10.1144/GSL.SP.2001.185.01.05.
16. Malkovets, V.G.; Rezvukhin, D.I.; Belousova, E.A.; Griffin, W.L.; Sharygin, I.S.; Tretiakova, I.G.; Gibsher, A.A.; O'Reilly, S.Y.; Kuzmin, D.V.; Litasov, K.D.; Logvinova, A.M.; Pokhilenko, N.P.; Sobolev, N.V. Cr-rich rutile: A powerful tool for diamond exploration. *Lithos* **2016**, *265*, 304–311, https://doi.org/10.1016/j.lithos.2016.08.017.
17. Natural Resources Canada. Available online: http://www.nrcan.gc.ca/mining-materials/publications/17762 (accessed on 15-11-2018).
18. McClenaghan, M.B. Indicator mineral methods in mineral exploration. *Geochem.: Explor., Environ., Anal.* **2005**, 5, 233–245, https://doi.org/10.1144/1467-7873/03-066.
19. McClenaghan, M.B.; Thorleifson, L.H.; DiLabio, R.N.W. Till geochemical and indicator mineral methods in mineral exploration. *Ore Geol. Rev.* **2000**, *16*, 145–166, https://doi.org/10.1016/S0169-1368(99)00028-1.
20. Averill, S.A.; Zimmerman, J.R. The riddle resolved: The discovery of the Partridge gold zone using sonic drilling in glacial overburden at Waddy Lake, Saskatchewan. *Canadian Geology Journal of the Canadian Institute of Mining and Metallurgy* **1986**, *1*, 14-20.
21. Sopuck, V.J.; Schreiner, B.T.; Averill, S.A. Drift prospecting for gold in Saskatchewan – use of heavy mineral concentrates in tills. In Gold in the Western Shield; Clark, L.A., Ed; *Can. Inst. Min. Metall.* Special Volume 38, **1986**, 435–469.
22. Huhta, P. Studies of till and heavy minerals for gold prospecting at Ilomantsi, eastern Finland. In Prospecting in Areas of Glaciated Terrain; MacDonald, D.R., Mills, K.A., Eds; Canadian Institute of Mining and Metallurgy, **1988**, 285–292.
23. Huhta, P. The use of heavy mineral concentrates from till in gold exploration in the late Archean Hattu Schist belt, Ilomantsi, Eastern Finland. Geological Survey of Finland, Special Paper 17, **1993**, 363–372.
24. Bernier, M.A.; Webber, G.R. Mineralogical and geochemical analysis of shallow overburden as an aid to gold exploration in southwestern Gaspésie, Quebec, Canada. *J. Geochem. Explor.* **1989**, *34*, 115–145, https://doi.org/10.1016/0375-6742(89)90096-4.
25. Nikkarinen, M. Size, form and composition of gold grains in glacial drift in Ilomantsi, eastern Finland. *J. Geochem. Explor.* **1991**, *39*, 295–302, https://doi.org/10.1016/0375-6742(91)90018-P.

26. Saarnisto, M.; Tamminen, E.; Vaasjoki, M. Gold in bedrock and glacial deposits in the Ivalojoki area, Finnish Lapland. *J. Geochem. Explor.* **1991**, *39*, 303–322, https://doi.org/10.1016/0375-6742(91)90019-Q.
27. Sarala, P.; Pulkkinen, E.; Ojala, V.J.; Peltoniemi-Taivalkoski, A. Gold exploration using till at Petäjälehto, northern Finland. *Geochem.: Explor., Environ., Anal.* **2009**, 9, 247–255, https://doi.org/10.1144/1467-7873/09-187.
28. Taivalkoski, A.; Sarala, P.; Hulkki, H. Gold exploration using heavy minerals in till and weathered bedrock in Petäjäselkä, northern Finland. *Geochem.: Explor., Environ., Anal.* **2015**, *15*, 205–221, https://doi.org/10.1144/geochem2014-288.
29. Wang, W.; Poling, G.W. Methods for recovering fine placer gold. *Can. Inst. Min. Metall. Bull.* **1983**, *76*, 47–56.
30. Giusti, L. The morphology, mineralogy, and behavior of "fine-grained" gold from placer deposits of Alberta: sampling and implications for mineral exploration. *Can. J. Earth Sci.* **1986**, 23, 1662–1672, https://doi.org/10.1139/e86-154.
31. Nichol, I.; Lavin, O.P.; McClenaghan, M.B.; Stanley, C.R. The optimization of geochemical exploration for gold using glacial till. *Explor. Mining Geol.* **1992**, *1*, 305–326.
32. Sibbick, S.J.; Fletcher, W.K. Distribution and behavior of gold in soils and tills at the Nickel Plate Mine, southern British Columbia, Canada. *J. Geochem. Explor.* **1993**, *47*, 183–200, https://doi.org/10.1016/0375-6742(93)90065-T.
33. Mitchell, C.J.; Evans, E.J.; Styles, M.T. A review of gold particle-size and recovery methods. British Geological Survey Technical Report WC/97/14, **1997**.
34. Dilabio R. N. W. *Classification and interpretation of the shape and surface textures on the Canadian Shield.* In: Current Research, Part C, Geological Survey of Canada, **1990**, Paper 90-1C, p. 323-329.
35. Clifton, H.E.; Hunter, R.E.; Swanson, F.J.; Philipps, R.L. Sample size and meaningful gold analysis. U.S. Geological Survey Professional Paper 625-C, **1969**, C1–C17.
36: Girard R., Tremblay J., Néron A., Longuépée H., **2021**. Automated gold grain counting: Part 2: What size and shape can tell!. Minerals, this issue.
37. Girard R., Tremblay J., Néron A., Longuépée H., **2021**. Automated gold grain counting: Part 3: What chemistry can tell!. Minerals, this issue.
38. Frimmel, H.E. Earth's continental crustal gold endowment. *Earth Planet. Sc. Lett.* **2008**, *267*, 45–55, https://doi.org/10.1016/j.epsl.2007.11.022.
39. Goldfarb, R.J.; Groves, D.I. Orogenic gold: Common or evolving fluid and metal sources through time. *Lithos* **2015**, *233*, 2–26, https://doi.org/10.1016/j.lithos.2015.07.011.
40. McQueen, K.G.; Bielin, S.; Lennie, C.A. The nature of pyritic gold ores at Kalgoorlie, Western Australia: geological and metallurgical implications. James Cook University of North Queensland, Contributions of the Economic Geology Research Unit 51, 42 pp.
41. Dominy, S.C.; Xie, Y.; Platten, I.M. Characterisation of in situ gold particle size and distribution for sampling protocol optimisation. Ninth International Congress for Applied Mineralogy, Brisbane, Australia, 8-10 September **2008**, 175–185.
42. Grammatikopoulos, T.A.; Porritt, L.; Petersen, J.S.; Christensen, K. Mineralogical characterisation and process mineralogy of goldbearing rocks from the Nalunaq gold deposit, Greenland. *App. Earth Sc.* **2004**, *113*, 197–203.
43. Haycock, H.M. The role of the microscope in the study of gold ores. *Can. Inst. Min. Metall.* **1937**, 40, 405–414.
44. Harris, D.C. The mineralogy of gold and its relevance to gold recoveries. *Miner. Deposita* **1990**, *25*, S3–S7.
45. Dominy, S.C.; Platten, I.M. Gold particle clustering: a new consideration in sampling applications. *Applied Eath Science* **2007**, *116*, 130–142, https://doi.org/10.1179/174327507X207474.
46. Dominy, S.C.; O'Connor, L.; Glass, H.J.; Xie, Y. Geometallurgical study of a gravity recoverable gold orebody. *Minerals* **2018**, *8*, 186, https://doi.org/10.3390/min8050186.
47. Joralemon, P. The occurrence of gold at the Getchell Mine, Nevada. *Econ. Geol.* **1951**, *46*, 267–310, https://doi.org/10.2113/gsecongeo.46.3.267.
48. Palenik, C.; Utsunomiya, S.; Reich, M.; Kesler, S.E.; Wang, L.; Ewing, R.C. "Invisible" gold revealed: Direct imaging of gold nanoparticles in a Carlin-type deposit. *Am. Mineral.* **2004**, *89*, 1359–1366, https://doi.org/10.2138/am-2004-1002.

49. Healy, R.E.; Petruk, W. Petrology of Au-Ag-Hg alloy and "invisible" gold in the Trout Lake massive sulfide deposit, Flin Flon, Manitoba. *Can. Min.* **1990**, *28*, 189–206.
50. Gregory, M.J.; Lang, J.R.; Gilbert, S.; Olson Hoal, K. Geometallurgy of the Pebble copper-gold-molybdenum deposit, Alaska: implications for gold distribution and paragenesis. *Econ. Geol.* **2013**, *108*, 463–482.
51. Kyle, J.R.; Mote, A.S.; Ketcham, R.A. High resolution X-ray computed tomography studies of Grasberg porphyry Cu-Au ores, Papua, Indonesia. *Miner. Deposita* **2008**, *43*, 519–532.
52. Cabri, L.J.; Beattie, M.; Rudashevsky, N.S.; Rudashevsky, V.N. Process mineralogy of Au, Pd and Pt ores from the Skaergaard intrusion, Greenland, using new technology. *Minerals Engineering* **2005**, *18*, 887–897.
53. Wang Y., McClung C., Lin C.L., Miller J.D., **2018**. *Stereological corrections of perimeter based estimates of exposed grain surface area*. Mineral Engineering, V.125, Pp. 64-73
54. Haggerty S.E.,. Micro-diamonds: Proposed origins, crystal growth laws, and the underlying principle governing resource predictions. Geochimica and cosmochimica acta. **2019**, Vol 266, pp. 184-196
55. dos Santos Alves, K., Sanchez S.B., Barreirao J.G., Polomares R.M., Prieto J.M.C.,. *Morphological and composition; analysis of alluvial gold: The Fresnedoso gold placer (Spain).* Ore Geology Reviews, **2020**, V. 121 (103489)
56. Rogers J.J., *Detection of lognormal size distributions in clastic sediments*. Journal of sedimentary petrology, **1959**. V.29, No.3, pp.402-407.
57. Bergman R.B., Bill A. On the origin of logarithmic-normal distributions: An analytical derivation and its application to nucleation and growth processes. Journal of Crystal Growth. **2008**, Vol 301, pp. 3135-3138
58. Kretz R. Grain-size distribution for certain metamorphic minerals in relation to nucleation and growth. Journal of Geology, **1966**, Vol 74, no 2, pp xxx
59. Girard R. *Detrital Gold: Down to the micrometer!* Geological Association of Canada-Mineralogical Association of Canada. Annual meeting, Abstract. **2016**
60. DiLabio, R.N.W. Gold abundances vs. grain size in weathered and unweathered till. Geological Survey of Canada, Paper 85-1A, **1985**, 117–122.
61. DiLabio, R.N.W. Residence sites of gold, PGE, and rare lithophile elements in till. In Prospecting in Areas of Glaciated Terrain; MacDonald, D.R., Mills, K.A., Eds; Canadian Institute of Mining and Metallurgy, **1988**, 121–140.
62. Breton, W.E.; Briggs, D.N.; Rollinson, J.P. Till prospecting in the area of the Farley Lake gold deposits, northwestern Manitoba, Canada. In Prospecting in Areas of Glaciated Terrain; MacDonald, D.R., Mills, K.A., Eds; Canadian Institute of Mining and Metallurgy, **1988**, 225–239.
63. McClenaghan, M.B. Regional and local-scale gold grain and till geochemical signatures of lode Au deposits in the western Abitibi Greenstone Belt, central Canada. In Drift Exploration in Glaciated Terrain; McClenaghan, M.B., Bobrowsky, P.T., Hall, G.E.M., Cook, S.J., Eds.; *Geol. Soc. London, Spec. Publ.* **2001**, 185, 201–224, https://doi.org/10.1144/GSL.SP.2001.185.01.09.
64. McClenaghan, M.B.; Plouffe, A.; McMartin, I.; Campbell, J.E.; Spirito, W.A.; Paulen, R.C.; Garrett, R.G.; Hall, G.E.M. Till sampling and geochemical analytical protocols used by the Geological Survey of Canada. *Geochem.: Explor., Environ., Anal.* **2013**, *13*, 285–301, http://dx.doi.org/10.1144/geochem2011-083.
65. Plouffe, A.; McClenaghan, M.B.; Paulen, R.C.; McMartin, I.; Campbell, J.E.; Spirito, W.A. Processing of glacial sediments for the recovery of indicator minerals: protocols used at the Geological Survey of Canada. *Geochem.: Explor., Environ., Anal.* **2013**, *13*, 301–316, https://dx.doi.org/10.1144/geochem2011-109.
66. Fandrich, R.; Gu, Y.; Burrows, D.; Moeller, K. Modern SEM-based mineral liberation analysis. *Int. J. Miner. Process.* **2007**, *84*, 310–320, https://doi.org/10.1016/j.minpro.2006.07.018.
67. Landsberg, G.S., 1976. Optics. MIR, Moscow, 926 pages.
68. Loebich, O. The optical property of gold. **1972**, Gold Bulletin vol. 5 (1), 2-10.
69. Néron A., Girard R., Bédard L.P. *Automated optical gold grain counting: A quantum leap.* Geological Association of Canada-Mineralogical Association of Canada. **2017.** Annual meeting, Abstract.

70. Néron A., Girard R., Bédard L.P. *ARTPhot: Automated routine for grain counting using a digital microscope and a neural network.* Geological Association of Canada-Mineralogical Association of Canada. **2018**. Annual meeting, Abstract.
71. SZEGEDY, C. et al., **2017**. Inception-V4, Inception-ResNet and the Impact of Residual Connections on Learning. Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence (AAAI-17) (pp. 4278-4284).
72. Boivin, J.-F., Bédard, L.P. and Longuépée, H., Submitted. Counting a pot of gold: a till golden standard. J. Geochemical Exploration. Dunkl I., von Eynatten H., Ando S., Lunsdorf K., Morton A., Alexander B., Aradi L., Augustsson C., Bahlburg H., Barbarano M., Benedictus A., Berndt J., Bitz I, Boekhout F, Breitfeld T., Cascalho J., Costa P.J.M., Ekwenye O., Feher K, Flores-Aqueveque V, Fuhring P., Giannini P., Goetz W., Guedes C, Gyurica G, Hennig-Breitfeld J., Hulscher J., Jafarzadeh M., Jagodziński R., Jozsa S., Kelemen P., Keulen N., Kovacic M., Liebermann C., Limonta M., Lužar-Oberiter B., Markovic F., Melcher F., Miklos D.G.,, Moghalu O., Mounteney I., Nascimento D., Novaković T., Obbagy G., Oehlke M., Omma J., Onuk P., Passchier S., Pfaff K., Linconir L.P., Power M., Razum I., Resentini A., Sagi T., Salata D., Salgueiro R., Schonig J., Sitnikova M., Sternal B., Szakmany G., Szokaluk M., Thamo-Bozso E., Toth A., Tremblay J., Verhaegen J., Villasenor T., Wagreich M., Wolf A., Yoshida K.,. *Comparability of heavy mineral data – The first interlaboratory round robin test*. **2020**. Earth Science Reviews, vol 211 (103210)
73. Percival, J.A.; McGrath, P.H. Deep crustal structure and tectonic history of the Northern Kapuskasing Uplift of Ontario: An integrated petrological-geophysical study. *Tectonics* **1986**, *5*, 553–572, https://doi.org/10.1029/TC005i004p00553.
74. Bursnall, J.T.; Leclair, A.D.; Moser, D.E.; Percival, J.A. Structural correlation within the Kapuskasing uplift. *Can. J. Earth Sci.* **1994**, *31*, 1081–1095, https://doi.org/10.1139/e94-097.
75. Percival, J.A.; West, G.F. The Kapuskasing uplift: a geological and geophysical synthesis. *Can. J. Earth Sci.* **1994**, *31*, 1256–1286, https://doi.org/10.1139/e94-110.
76. Heather, K.B.; Percival, J.A.; Moser, D.; Bleeker, W. *Tectonics and metallogeny of Archean crust in the Abitibi-Kapuskasing-Wawa region*; Geological Survey of Canada, Open File 3141, **1995**.
77. Krogh, T.E. High precision U-Pb ages for granulite metamorphism and deformation in the Archean Kapuskasing structural zone, Ontario: implications for structure and development of the lower crust. *Earth Planet. Sc. Lett.* **1993**, *119*, 1–18, https://doi.org/10.1016/0012-821X(93)90002-Q.
78. Leclair, A.D.; Ernst, R.E.; Hattori, K. Crustal-scale auriferous shear zones in the central Superior province, Canada. *Geology*, **1993**, *21*, 399–402, https://doi.org/10.1130/0091-7613(1993)021<0399:CSASZI>2.3.CO;2.
79. Moser, D.E. The geology and structure of the mid-crustal Wawa gneiss domain: a key to understanding tectonic variation with depth and time in the late Archean Abitibi–Wawa orogen. *Can. J. Earth Sci.* **1994**, *31*, 1064–1080, https://doi.org/10.1139/e94-096.
80. Moser, D.E.; Bowman, J.R.; Wooden, J.; Valley, J.W.; Mazdab, F.; Kita, N. Creation of a continent recorded in zircon zoning. *Geology* **2008**, *36*, 239–242, https://doi.org/10.1130/G24416A.1.
81. Dzick, W. Probe Mines Limited: Mineral resource estimate update Borden gold project: NI43-101 Technical Report, **2014**.
82. LaFontaine, D. Structural and Metamorphic Control on the Borden Gold Deposit, Chapleau, Ontario. M.Sc. Thesis, Lakehead University, Thunder Bay, ON, Canada, **2016**.
83. Goldcorp Inc. Available online: http://www.goldcorp.com (accessed on 15-11-2018).
84. Gao, C. *Results of regional till sampling in the Chapleau area, northern Ontario*; Ontario Geological Survey, Open File Report 6320, *2016*.
85. Girard, R.; Villeneuve, P. Regional till survey on East Limb, Borden South, and Borden properties, Chapleau area, Ontario; IOS Services Géoscientifiques Inc. for Goldcorp Borden Ltd., **2018**; 416 pp.
86. Girard R., Villeneuve P., **2016**. *Till sampling campaign, Chapleau-Foleyet Area, Ontario.* IOS Services Géoscientifiques Inc. Private report presented to Goldcorp Borden Ltd., 541 p.
87. Girard R., Villeneuve P., **2017**. *Regional till survey on Landrienne patented claims and Orientation survey on Borden Gold deposit.* IOS Services Géoscientifiques Inc. Private report presented to Goldcorp Borden Ltd., 1659 p.
88. Girard R., Villeneuve P., **2017**. *Till sampling campaign, Chapleau-Foleyet area, Ontario.* IOS Services Géoscientifiques Inc. Private report presented to Goldcorp Borden Ltd., 381 p.

 doi:10.20944/preprints202102.0186.v1

89. Girard R., Villeneuve P., **2018**. *Interpretation of Sonic drilling campaign, Chapleau-Foyelet area, Ontario*. IOS Services Géoscientifiques Inc. Private report presented to Goldcorp Borden Ltd., 534 p.
90. Boivin J.F., Bédard L.P., Longuépée H., **2021** (submitted), *Counting a pot of gold: a till golden standard*. Journal of Geochemical Exploration.